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AN INVESTIGATION OF PROJECT
MANAGEMENT TECHNIQUES FOR SCHEDULING
RAAF DEPOT LEVEL MAINTENANCE

THESIS

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THESIS

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Preface

In this paper I have attempted to examine and document the difficulties of assessing comparative performances and capabilities of commercial project network scheduling software. The paper is based in part on the experience of the RAAF in selecting a suitable microcomputer package for scheduling the maintenance tasks of aircraft Depot Level Maintenance. As such, I have sought to assess the performance of some commercial microcomputer software for the RAAF by comparing the project Total Durations of optimal solutions with those generated by the commercial software, for a series of relatively small problem sets. Comparative software assessments indicated that the practitioner could make savings in scheduled project durations of more than 30% by choosing the most applicable scheduling software for a particular application. I also investigated the use of regression models to predict the performance of the scheduling software packages when confronted with particular network problems.

However, during the research for this paper, I became interested in the question of how practical were the schedules produced by the usual analyses of networks. The real world of industry thrusts variabilities in project task durations at the manager which are not well accounted for in the usual approaches of commercial software. The last parts of this paper therefore raise a series of questions on the robustness of optimal and current heuristic schedules which are the scheduling engines of commercial packages. There is currently embryonic research using principles of the Theory of Constraints which may prove to provide schedule practicality, or robustness.

The reader may note that my spelling and word usage in this paper conforms to the Oxford Dictionary rather than the local Websters' Dictionary. In all cases of differences detected during preparation, the variations were found to be only cosmetic and should not cause confusion of meaning to the reader.

Whilst writing this thesis I had notable assistance from others. I wish to thank sincerely Major Paul Auclair for his enthusiasm and guidance, and Captain Wendell Simpson for his technical assistance on Patterson's problem set.

Of course my efforts would not have been possible without the unswerving understanding and support of my wife, Ruth. Although very distant from AFIT, I must also acknowledge a debt to my parents for their encouragement of my endeavours.

Kerry M. Bayley

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Abstract

This research investigates the scheduling performance of commercial project management software packages. The research was instigated in part by the difficulties that the Royal Australian Air Force (RAAF) experienced in evaluating the comparative performance of microcomputer-based software scheduling packages for use in scheduling the maintenance tasks of RAAF aircraft undergoing Depot Level Maintenance (DLM).

A literature review revealed that while much research had been published on the performances of project scheduling techniques, only one paper could be found quantifying commercial software performances. Further, the published literature had very few assessment metrics or test data in common.

Performances of several commercial software packages were investigated, using the closeness to the schedule's optimally minimum Total Duration as the performance measure, and the set of 110 single network resource constrained problems by Patterson as the test data. The performances showed that no one package performed best on all problems. On average, the best package produced schedules 5.2% longer than the optimal schedule length, with values ranging from 0% to 35% over the 110 problems, and 95 of 110 problems in the range 0% to 10% above optimal. The worst package

produced schedules 14.1% longer than the optimal, on average.

Given the variability in performances of commercial software, a means to better match scheduling software to network problem types was proposed. Through regression analysis of scheduling results from each software package and 58 network measures of the 110 problem set, first order mathematical models were proposed. The models predicted software scheduling performance, in terms of the predicted schedule length for each software package. Inputs to the models were two network characteristics: SADUR (sum of all task durations) and ACONMX (maximum resource constrainedness using all activities as a base).

Most project scheduling software is based on the assumption that the project's task durations have negligible variability. However, the practical world of industry deals with ever changing durations. A series of simulation were run to examine the robustness of the optimal static scheduling solution in a dynamic environment. The results show that projects will, on average, run longer than scheduled.

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I. Introduction

General Issue

The Royal Australian Air Force (RAAF) carries out Depot Level Maintenance (DLM) on many of its aircraft at RAAF operated maintenance units. These units and their Commands have effective forecasting and scheduling systems to determine the dates that individual aircraft are to commence DLM servicings. They also have effective forecasting systems to determine what maintenance tasks are to be performed during each of the aircraft DLM servicings. However, the RAAF has become concerned with the apparent ineffectiveness of current methods for scheduling the hundreds of maintenance tasks within each of the aircraft DLM servicings (37:1). These concerns have arisen due to increases in the durations of some recent aircraft DLM servicings and a widespread drive by the Australian Department of Defence to increase productivity. Longer DLM durations consume additional maintenance manpower and facilities which the RAAF can ill afford.

Over the years, the RAAF has used a number of techniques to schedule tasks within each individual DLM servicing. These have ranged from simple manual checklists, to a number of Gantt charting systems, to some preliminary work on Critical Path Analysis (CPA). The preliminary CPA work was carried out for F-111 aircraft servicings at No 3 Aircraft Depot RAAF Base Amberley by a RAAF Work Study Consultancy Group (WSCG). The group modelled the tasks of the servicing as nodes on a project network. Using the common project management techniques of deterministic, resource constrained CPA, the group produced a workable time-based task schedule because the characteristics of the tasks matched the assumptions of CPA. Specifically, each task had fixed task precedences, approximately fixed task duration and approximately fixed resource consumptions.

As a follow-on to this work in October 1990, the RAAF commenced a trial using commercial CPA software to generate task schedules for aircraft DLM servicings at a number of selected RAAF DLM facilities. This trial has been named the RAAF Aircraft Servicing and Planning System (ASPS)(30). The microcomputer-based, commercially available software package selected for use in the trial is X-Pert by Microplanner.

When assessing which commercial "off the shelf" software package to use for the ASPS trial, the RAAF found few performance standards available with which to compare packages. This resulted in the RAAF's selection being based more on qualitative than quantitative factors. One of the aims of this paper is to assess quantitatively the performance of the scheduling package selected by the RAAF.

Performance of Project Scheduling Techniques

There are numerous methods used by researchers to assess the performance of project scheduling techniques. Examples include solution computation time and comparison of computed schedules to the optimal solution results. A common measure used when comparing techniques to the optimal is the Total Duration time of the project, which is the time elapsed from commencement of the project's first task to completion of the project's last task. The closer a scheduling technique's Total Duration is to the duration of the optimal solution, then the more accurate that technique is considered to be.

Current research provides solutions to network scheduling problems but many are under assumptions that do not reflect well the operational realities. Scheduling practitioners must therefore be careful when using the theoretically optimal solution. The optimal solution is the best scheduling solution only if all the assumptions of the scheduling technique are met. For example, optimal solutions calculated to minimise Total Durations assume task durations are fixed, that is, deterministic. In practice, aircraft DLM servicing task durations are subject to variations, making them not truly deterministic. Thus, the optimal scheduling solutions, approximated with commercial software, may not correspond well to the actual scheduling problems faced by the maintenance personnel at RAAF DLM facilities.

Specific Problems

The RAAF wishes to improve the scheduling of DLM servicing tasks through the use of microcomputer-based commercial project management software. The ASPS trial has chosen the Microplanner X-Pert software package to produce a schedule of maintenance tasks for DLM of most of its aircraft types. However, the RAAF is not readily able to quantify the scheduling performance of this or any other commercial package available.

Additionally, if the trial is successful, the RAAF is considering expanding the use of CPA into other areas of maintenance planning. This gives rise to three problem areas for the RAAF.

The first is a short term problem. It is to make a general quantitative comparative assessment of several commercial network scheduling packages to determine their scheduling strengths and weaknesses, so that the ASPS teams may have confidence (or otherwise) in their chosen software. The second is a longer term problem. It is to provide a methodology for predicting the schedulers' performance given the particular characteristics of networks to be solved. This would enable the RAAF to select the best scheduler for a particular application, or alternatively, the scheduler which performs best over a range of applications. The third is a much longer term issue which is a more fundamental research problem. It is the need to explore the currently implicit assumption that the optimal solution to the CPA network is actually the best schedule in a real world scheduling environment. Such an exploration would necessarily encompass the issue of schedule robustness under the daily changes of individual task durations, that is, how well the schedules predict the actual completion times of the whole project. Also, the real world involves the concept of dynamic scheduling, that is, revising project schedules as the project progresses.

Research Questions

A number of questions naturally arise from the RAAF's decision to use commercial project management software to schedule its DLM servicing tasks. The questions addressed by this research effort are:

1. How much does the duration of the schedule produced by commercial scheduling packages deviate from the optimal solution? Specifically, how do the scheduling solutions produced by the software package on trial with the RAAF ASPS, X-Pert by Microplanner, compare with other commercial software solutions and the corresponding optimal solution?

2. Can the performance of a software package be predicted by specifying the type of network problem that is to be solved?

3. If the performance can be predicted, what characteristics of the network are most significant?

4. How do the optimal and commercial package scheduling solutions, based on the assumption of deterministic task durations, withstand the practicalities of task duration variabilities and hence dynamic rescheduling?

General Methodology

This paper investigates the question of scheduling performance in three distinct steps.

Optimal Solution Comparison. The performance of Microplanner X-Pert is quantified by comparing the Total Duration of the schedules it produces with the corresponding Total Durations produced by six other commercial software packages and the optimal solution. Patterson's collection of 110 network problems (25:860) is used as the test data for the schedule comparisons.

Scheduler Performance Prediction Model. To further investigate the performance of each scheduling package, the characteristics of each of Patterson's problems are examined against the Total Durations produced by each software package. To achieve this, a multiple linear regression analysis is used to describe the Total Duration in terms of descriptive parameters for each of Patterson's networks.

Optimal Solution Robustness in the Dynamic Environment. A simple approach is used to investigate the robustness of the optimal solution in the practical world, such as the DLM servicing facility. A small network is chosen and then scheduled in four different ways. Two of the schedules result from using an optimal solution generator, Talbot's Optimiser (25:858). The remaining two schedules result from applying Microplanner Professional. Each scheduling package will produce two schedules. One will be a normal schedule produced by such application software, that is, a static schedule, whilst the other will result from dynamic scheduling.

Scope of Research

There are potentially many ways to consider solving the task scheduling problems that arise in servicing aircraft at DLM. However, the use of project management network techniques may be applied readily to aircraft DLM, as has been the case with the RAAF (30:1), the United States Air Force (USAF)(22), and commercial airlines (35). Such usage abounds despite the fact that traditional project management and scheduling literature does not readily consider the use of project management techniques in the field of aircraft maintenance task scheduling. For example, Roman considers project management techniques apply only to "noncycled activities" within "ad hoc organisational arrangements" (29:xvii), which is clearly the opposite of routine aircraft

DLM servicing processes. However, the basic requirements for project network usage, as discussed by Chase and Aquilano (2:481), are met by RAAF aircraft maintenance philosophy. That is, RAAF maintenance tasks are well defined, may be commenced or finished independently in the schedule, and have precedence relationships defining their order of execution.

Other scheduling techniques such as traditional job shop and flow shop are conceptually much more difficult to apply to the whole aircraft DLM problem, as they do not cope well with the disassembly/assembly processes and the need for scheduling several resources on each task (5:304). Additionally, job and flow shop techniques have not been found to be used by the aircraft DLM industry in practice (28; 35). Consequently, job and flow shop techniques have not been considered in this paper.

Only limited quantities of resources such as manpower, support equipment and facilities are available to complete the servicing tasks on aircraft DLM. It is therefore essential to consider the network representation to have finite resources. In practice, it is the resources which usually constrain the progress of RAAF aircraft DLM servicings. Therefore, the added constraints of task completion dates, or due dates, generally are not imposed on the network. Hence, the class of problems for consideration in this paper will be constrained, multiple resource, network problems.

A further assumption made is that the resources for individual tasks have a constant demand throughout the task duration. For example, if a task requires three workers, then the resource demand is three workers per day for every day from task start until task completion. Resources available are also assumed to be constant. If the available resource is five workers per day, then a total of five workers are available per day for every day of the project.

Generally, RAAF DLM hangar facilities are organised so that technicians are assigned to a particular aircraft which is undergoing DLM servicing. That is, when an aircraft commences its servicing a team of technicians and other resources are specifically assigned to that servicing. The technicians and other resources carry out all the servicing tasks and remain assigned to that aircraft until the servicing is completed. Additionally, once tasks are commenced they usually are not interrupted, or able to be split. Thus, the servicing of an individual aircraft is assumed to be a single network project with non-interrupted, non-split tasks which use multiple fixed level resources.

There are several optimal solution techniques available, such as those by Davis, Stinson or Talbot (25:855), to find and verify the minimum duration schedule of resource-constrained network problems. By definition, each of these solution techniques will produce solutions with identical Total Durations, although the schedules themselves may differ. Although the choice of optimal solution techniques is somewhat arbitrary, this paper will use only Talbot's technique, as it has been discussed frequently in the literature of interest and solution computer code was available.

There are many heuristic (rule-of-thumb) solution techniques described and tested in the literature. However, which of these techniques are used in the commercial packages cannot be determined due to the proprietary nature of commercial software. Consequently, this paper must rely heavily on the scheduling solutions generated from each of the software packages themselves, rather than the extensive published scheduling literature or other non-commercial academic software.

In this paper seven commercial software packages are considered: Super Project Expert 1.0, Timeline 2.0, Timeline 4.0, Harvard Total Project Manager II, Primavera 4.0, Microplanner Professional 7.3b and Microplanner X-Pert. The first five are chosen as some scheduling performance information has already been compiled by Johnson (18:1). Microplanner X-Pert is included as this is the software currently under trial with ASPS (11:1). Microplanner Professional is included as it is already used by the RAAF in other areas of project scheduling (36).

However, for practical purposes this paper actually considers six packages: Super Project Expert 1.0, Timeline, Harvard Total Project Manager II, Primavera 4.0, Primavera 4.0 (SBL) and Microplanner Professional 7.3b. Johnson reports that Timeline 2.0 and Timeline 4.0 are identical, and that Primavera 4.0 produces differing schedules with the "Schedule Before Level (SBL)" option selected (18:4). Microplanner λ-Pert is reported to produce identical solutions to Microplanner Professional (16).

The performance of the software packages is documented in terms of one parameter, Total Duration, which is the total scheduled duration of the project. Resource utilisation parameters will not be considered in this paper because project duration is the most significant factor in the RAAF DLM servicing, given the initial assumption that fixed resources are allocated to the servicing for the duration of the servicing. However, the performance measure is not complete without an accompanying analysis of the network that is to be scheduled. To that end, the paper uses 58 network descriptive measures from current literature, as summarised in Simpson's work (33:203-217). They include measures of the network calculated before and after identification of the critical path.

This paper does not attempt to characterise the type of network which best represents the activities of RAAF aircraft undergoing DLM servicing. The ASPS trial is still in its infancy and so insufficient data is currently available to draw valid conclusions. Accordingly, the project network structures under consideration for this paper are left as broad as possible. They are represented by the set of 110 network problems that Patterson has assembled (25:860). This problem set has numbers of network activities ranging from 7 to 50, with the number of resources required per activity ranging from one to three. Appendix A gives a more complete description of the problem set.

This paper does not investigate superior ways to perform individual maintenance tasks on aircraft. The tasks are assumed to be previously determined with the characteristics of duration, precedence relationships and resource requirements. Furthermore, no attempt is made to improve the means by which servicing tasks are generated, documented or acquitted.

II. Background

The background first provides a brief description of project scheduling techniques and their historical development. A more detailed literature review then examines the use of optimal and heuristic solution techniques, and also the use of optimality as the measure of project task scheduling performance. Finally, an insight is given into the means by which the RAAF carries out aircraft DLM servicings.

Scheduling

General. The production of goods or services involves many individual tasks of manufacture, construction and testing. Sequencing of these tasks is not necessarily rigid. Consequently, the possible number of task sequence permutations can easily become extremely large. Each permutation may have a different result on the productivity, duration and profitability of the whole project. The requirements for good scheduling decisions can therefore easily exceed the ability of the unaided human scheduler.

The majority of common project scheduling techniques are based on the Program Evaluation and Review Technique (PERT), the Critical Path Method (CPM), and Gantt charting. Each of these techniques calculates an estimated duration for a project, given the constraints of the project network.

Gantt Chart. The first of the modern project management techniques is known as the Gantt Chart. It was first documented in 1914 by Henry L. Gantt (2:19). This technique simply displays tasks with their start and end points against a time line. The planned and actual task completion times are compared progressively throughout the project. Since its first appearance, the technique has been enhanced by adding some task dependency notations and elementary resource tracking. However, the Gantt technique does not adequately address the issue of network activity precedence, except in relatively trivial cases. Indeed, Chase and Aquilano assert that the Gantt chart is difficult to use when there are more than 30 activities in a network (2:483). Gantt charting should therefore not be considered seriously as the basis for scheduling complex projects, despite the fact that most project managers do not progress past the use of Gantt charts (29:162). Indeed, the issue is further blurred as the Gantt chart is often used to display schedule and resource information in PERT and CPM based packages (13:338).

Program Evaluation and Review Technique. A major breakthrough in project management was the Project Evaluation and Review Technique (PERT) developed in 1958 under the sponsorship of the US Navy Special Projects Office for the Polaris submarine programme (2:481). PERT views the project as a network of related tasks. Each task is assigned a stochastic (probabilistic) duration and can only be started after its logical predecessor has finished. After the network is scheduled it is possible to give the user a probabilistic assessment of the Total Duration. In practice, the assessment usually calculated is for the project's critical path. Little emphasis is placed on resource issues.

As PERT takes a stochastic view of task duration times, an initial problem for the user has been to determine a suitable probability distribution to assign to each task's duration. Traditionally, unimodal Beta distributions have been used, calculated from user supplied estimates of minimum, maximum and most likely task duration times, although a number of variants have been considered (15:389). A further shortcoming of PERT has been that it makes the very broad assumption that activity durations are independent of each other. Also, it has often been assumed that the longest path through the stochastic PERT network will be the project critical path, such as in Kerzner (20:619). In fact, dependent on the characteristics of the particular network, many of the sub-critical paths may become the critical path at some time during the project by virtue of the stochastic nature of a PERT network. The likelihood of a sub-critical path becoming the critical path is dependant on how close the sub-critical and critical path lengths are and the variability of activity times on these paths.

Critical Path Method. Critical Path Method (CPM) was another network approach which evolved at approximately the same time as PERT. In 1957, Kelly of Remington-Rand and Walker of Du Pont developed CPM to improve maintenance shutdown procedures for chemical production plants (2:481). It uses a similar network representation to PERT, but unlike PERT, task durations are assumed to be deterministic (known accurately) and resource costs are considered. CPM calculates the longest path through the network and calls this the critical path. The critical path will not change for a given network because in CPM all activity durations remain constant.

Amalgamation of Network Methods. Some literature (29:146) and most commercial software packages do not clearly distinguish between the terms CPM and PERT for representation of network projects, as so many hybrid techniques have formed from the originals. A detailed account of this evolution has been documented by Weist (40:226). It therefore may be less confusing to refer to networks by specific individual qualifiers rather than the general terms of CPM and PERT. Accordingly, a network could be specified using some or all of the terms presented in Table 1.

To avoid confusion, this paper refers to the various PERT and CPM network representations of projects using the descriptors in Table 1.

Resource Issues. Each network project will consume resources of some kind. If the supply of a resource exceeds all demands placed on it by the network activities, then the resource is considered limitless or non-constraining. Usually, the real world has a finite quantity of resources available to projects for their completion. This means that at some points in the schedule the demand for resources by one activity, or a combination of several activities, may exceed the supply of the resource. In networks where this conflict occurs the resources are described as being constraining.

TABLE 1

DESCRIPTIONS OF PROJECT NETWORKS

CATEGORY	DESCRIPTORS	
Dimension	single project	multiproject
Representation	activity-on-node	activity-on-arrow
Activity Duration	deterministic split	stochastic non-split
Scheduling	static	dynamic
Resources	single constraining constant demand constant supply substitutable	multiple non-constraining variable demand variable supply non-substitutable
Activity Priority	preemption	non-preemption

The three traditional solutions to the problem of schedules with resource conflicts are to increase the supply of the resource, reduce the demand for the resource or move the timings of the competing activities so that the resource conflicts are eliminated. The preferred scheduling option, where possible, is to move the commencement of tasks within their slack or float time. Slack time of an activity is the amount of time that the commencement on an activity can be deferred without increasing Total Duration (3:297). However, if the activity must be moved outside the slack, then the critical path is lengthened, and hence Total Duration is increased.

Network Scheduling Solutions. The scheduling solution to a network is the sequence of activities which provides the "best" solution in terms of an optimising criterion. The most common criterion is to minimise the Total Duration while meeting the requirements of the network task precedences, activity durations, activity resource consumptions, and the level of resources available. Other optimising goals have included measures of project lateness, resource utilisation parameters, profit, costs, net present value and many others.

Optimality. The theoretically best solution is known as the optimal solution. So, in circumstances where minimising the Total Duration is the scheduling goal, the optimal solution will yield a theoretical schedule with the lowest possible Total Duration. However, current Total

Duration optimisers for resource constrained networks can only deal with relatively small network problems. The extensive computational requirements have limited the research literature on optimal scheduling to networks of approximately 50 tasks. Simpson's recent work confirms this problem. He states that a "linear increase in project size (number of activities, activity durations, number of precedence relationships, etc.) can be expected to generate an exponential increase in the solution times" of current exact solution procedures, known as optimisers (33:8). As a consequence of the computational limitations of optimal solutions and the assumption that the optimal solution is the practitioners' best schedule, there are hundreds of heuristics that have been developed to approximate the optimal solution (6:944). There have been scores of articles written comparing these heuristics to each other, and a few comparing heuristics to the optimal solutions. On average, the closest approximations by heuristics tend to have a Total Duration between five and ten percent higher than optimal (6:951).

A related assumption generally made in the literature is that the performance trends reported in comparisons of optimal solutions and heuristics for small problems are still valid for larger problems. Authors such as Davis and Patterson (6:953; 26:95) and Badiru (1:82) allude to the pitfalls in assuming that performances on small project networks are indicative of the performance on large projects. However, no real clarification of the issue could be found in the literature.

Problems Meeting Schedules. Despite advances of heuristics towards optimal solutions, practitioners continue to have difficulty routinely meeting schedules produced by these heuristics (32:66). The difficulty arises because the heuristic solutions are built on the initial assumptions, and hence limitations, of CPA networks. In particular, practitioners usually schedule under conditions of activity duration fluctuations, while assuming that activity durations remain constant. Surprisingly, few references could be found that discuss the practicality or robustness of CPA network analysis under field conditions. Schonberger (32:66-67) points out that both deterministic and stochastic critical path analysis schedules will almost invariably understate the actual Total Duration. In the deterministic case, real world delays in tasks will accumulate throughout the project thus increasing Total Duration. These delay times cannot be cancelled out by early performances in parallel paths. Schonberger (32:67) further postulates that the difference between actual Total Duration and the scheduled Total Duration will tend to be greater in networks with more parallel paths and those with more variability in task durations. Further, he says that in most stochastic analyses only one path is examined at a time and so the problems of merging paths are not fully addressed. The delayed paths are therefore not accounted for resulting in an underestimate of actual Total Duration, except for the most trivial of networks.

Although discussed in terms of manufacturing processes, Goldratt's Theory of Constraints (TOC) agrees with Schonberger's assertions regarding networks. Goldratt discusses how statistical fluctuations in sequence dependent tasks will inevitably cause an increase in process time (14:100,112). That is, a practitioner using current network schedules will inevitably experience a Total Duration greater than the optimal.

Research is currently under way by Cox and Pittman to adapt Goldratt's work to the area of resource constrained project network scheduling, although no work has been published yet. The research uses Goldratt's TOC to argue that the basis of CPA network analysis is flawed because it cannot adequately cope with the inevitable variabilities of the practical world. The work uses existing deterministic resource constrained project networks but the analysis differs. Instead of using traditional critical path analysis to minimise the Total Duration and then check for resource conflicts, a concept of network "critical chains" is used. The critical chain is the series of activity duration and resource combinations in the network which will ultimately constrain the Total Duration of the schedule. Once the critical chain is identified then the practitioner inserts time buffers into the network to ensure that the predicted schedule is very likely to be achieved in the somewhat unpredictable world of the practitioner. The schedule can be referred to as feasible-immune (4; 19; 27).

Comparative Assessment. Comparing performances of project scheduling techniques is extremely difficult because there are few standard metrics or test data sets that researchers or industry use. For example, Davis and Patterson (6:945) attempt an assessment by comparing the Total Duration of eight scheduling heuristics to an optimal solution, for 83 test problems. Ulusoy and Ozdamar (39:1151) use Extra Scheduled Time Ratio and a different 64 problem set to compare heuristics.

Badiru (1:88) is the only writer found who specifically addresses the problem of standardisation of scheduling performance measures. He compares the performance of 13 scheduling heuristics for 30 different test problems, using his three new metrics which are also based on the Total Duration time. Badiru's metrics quantify the comparative consistency of a number of heuristics in producing minimum Total Duration times for a number of problem types. He does not include optimal solutions in this comparison, presumably due to the limitations of network sizes that the optimal solution can calculate. Also, he does not offer a means to compare the measures used in other literature.

The lack of a standard set of test problems haunts the literature. Patterson's collection of 110 previously published problems is the closest that the literature approaches to a standard problem set. Appendix A gives more details of his problem set.

Although numerous writers (13; 23; 24) discuss the general features and capacities of commercial software, Johnson (18) was the only writer found to compare quantitatively the performance of commercial software packages. In an attempt towards standardisation, he scheduled the 110 problem set produced by Patterson with five commercial software packages and an optimum solution generator, Talbot's optimiser. He carried out a rudimentary analysis of the results by summing the 110 Total Duration times for each package and then comparing the sum to the result of the optimal solution. Given the importance to industry of the schedule produced by the commercial software products, and the lack of information available on the types of scheduling techniques used in these packages, it is surprising to find such a lack of articles published on this subject.

DLM Maintenance Procedures

Modern aircraft have complex systems which require considerable maintenance effort to ensure that they perform safely and reliably. Due to the nature of the industry, aircraft maintenance philosophy tends to be preventative, rather than to repair after failure. Consequently, scheduled preventative maintenance is an important consideration of maintenance costs. This places a considerable burden on aircraft maintenance planners to schedule maintenance tasks cost effectively.

To ensure minimum aircraft down time and most efficient maintenance effort, the RAAF carries out preventative maintenance tasks in bundles of activities called routine servicings. Each aircraft type has its components' maintenance requirements specified and documented, based on component flight criticality and expected failure rate. The maintenance requirements become physical tasks to be carried out at certain event accruals of the aircraft, such as every 500 flying hours or every two years. Maintenance tasks for all the aircraft's components are then grouped into bundles of tasks. These bundles become the routine servicings where major component replacements, modifications, testing and refurbishments are carried out. The most extensive preventative maintenance servicing performed on aircraft is known as Depot Level Maintenance (DLM)(7). To illustrate the size of a DLM servicing consider the RAAF C-130E DLM servicing carried out under contract by Air New Zealand. The servicing occurs once every three years, comprises at least 2200 individual tasks, utilises up to 20,000 manhours, and will last approximately 55 days (12).

The minimum maintenance tasks for RAAF aircraft servicings are determined by a central agency, RAAF Headquarters Logistics Command (RAAF HQLC). Tasks are arranged by aircraft system and technician's trade, in the approximate order of task commencement. However, responsibility for detailed task sequencing rests with the maintenance unit's Senior Engineering Officer (SENGO)(8). This is a practical consideration, as task sequencing may need to be changed from time to time, depending on the number and type of modifications, spares replacements or other special servicings required. In practice, the senior maintenance supervisor assigned to that particular aircraft for its servicing is made responsible to arrange the servicing's task schedule, in consultation with heads of the various technical trades involved. To manage the scheduling of the servicing, the maintenance supervisor usually has a standard Sequence Control Board (SCB). The standard SCB is a large wall mounted Gantt activity chart with a magnetic strip to represent each of the tasks to be performed, divided by technician's trade or aircraft system. The task dependency and durations are noted on the magnetic strips, based on accumulated unit scheduling experience (8; 9).

In the late 1980s, RAAF No 2 Aircraft Depot (2AD), at RAAF Richmond, developed an improved system of task scheduling using a project scheduling software package called MacProject. The unit realised that the growing complexity of major C-130 Hercules and P3 Orion servicings could not be scheduled and managed adequately using the SCB system. Although 2AD had some success with the system, for various reasons the application of CPA task scheduling to other RAAF maintenance facilities was not undertaken at that time.

Recently, RAAF No 3 Aircraft Depot (3AD), at RAAF Base Amberley, experienced increasing difficulties meeting the demand placed on the unit for completion of F-111 major servicings. The unit management realised that one of their problems was inadequate planning of the servicing contents. In 1990, to address the problems, the unit carried out preliminary work on the use of CPA techniques for their F-111 R5 servicing (the largest DLM servicing) task scheduling. Initially the unit used MacProject 1, but this was found to be inadequate for the size and complexity of the R5 because it did not adequately cope with constraining resources or use of sub-projects. The unit therefore upgraded to MacProject 2. However, before 3AD had completed their trial, the RAAF Work Study Consultancy Group (WSCG) commenced a study of the problems at 3AD (37:2). The WSCG recommended a number of improvements to maintenance procedures, including the continued use of CPA techniques for scheduling and managing the R5 servicing tasks. 3AD continued CPA modelling of an F-111 R5 servicing, with servicing tasks as nodes on the project network. In the network model, each of the servicing tasks had the attributes of fixed task precedences, fixed task duration and fixed resources consumption. Thus, the traditional project management techniques of deterministic, resource constrained CPA were used to produce a time-based aircraft servicing schedule.

The results of using CPA to schedule R5 servicing tasks at 3AD were immediate. The first servicing achieved a reduction in the Total Duration of 38% (38) from previous servicings. However, the reductions in Total Duration cannot be simply attributed to the CPA software itself. It is probable that the very process of preparing the data to be input to the CPA contributed most significantly to the reductions, although this is difficult to prove. Additionally, an increase in servicing productivity probably occurred because of the interest created by the WSCG study (that is, the phenomenon known as the "Hawthorne effect") (17:56-65). Collation of the R5 servicing information for input to MacProject was the first step in achieving servicing productivity improvements. Each subsequent scheduling performance improvement related to the CPA process becomes harder to obtain. At this point, the issue of scheduler software performance becomes more significant. If the software scheduler package used is inappropriate for the type of network being scheduled, selection of a more relevant scheduler could yield reductions in Total Duration of up to a further 30% (as shown in Chapter IV). This emphasises the importance of matching specific software capabilities to the particular scheduling problems. It also highlights the practical need for quantitative comparative metrics of scheduler performance.

When selecting a commercial software package for the ASPS trial, the RAAF faced several difficulties. Few performance standards were available with which to compare commercial packages. The available specification literature was mainly qualitative in nature. In particular, there was no information available to evaluate comparatively the task schedules produced by commercial software packages. As software producers were reluctant to divulge the exact scheduling techniques that their particular package utilised, academic literature could not be used to gauge the expected performance of the software. Ultimately, the software packages were assumed to have comparable scheduling performances. The comparative assessment was then made on the basis of less fundamental features such as computational speed, maximum number of activities, ease of usage, ease of learning, resource tracking, graphics interface, error handling capabilities, outputs, documentation, vendor support and cost. Thus, to date, the ability of the software to produce a highly desirable, time-based schedule of tasks has not been properly addressed.

Summary

The literature shows that, since the 1950s, the techniques for project management have evolved to form two distinct groups. The first is the Gantt chart based techniques, which are only suitable for small, simple projects. The second is the vast family of task networked techniques, which are hybrids of the original PERT and CPM techniques. Network techniques are effective in large projects with multiple task interdependency and resource constraints. Large network techniques are impractical to solve optimally due to computing requirements. Heuristics are therefore used to find scheduling solutions that have been reported to have Total Durations that average five to ten percent above the optimal solution for small networks. The heuristics used to provide scheduling solutions to the networks are numerous. There is great difficulty in comparing the performance of these heuristics, for there are no industry standard measurements or standard network problem sets. Compounding the difficulty is the fact that details of heuristics used in currently available proprietary computer packages cannot not be determined. The practical result is an inability to best match network problem types to commercial project scheduling software packages.

The literature infers that the optimal solutions are the best solutions both theoretically and in the practical world of industry. The experience of industry suggests otherwise. Schonberger and TOC practitioners state that assumptions of CPA analysis are inappropriate for projects with variable task durations.

III. Methodology

General Description

This paper investigated the question of project network scheduler performances, and hence aircraft DLM task scheduling, in three distinct steps. The first was a comparison of scheduler Total Durations produced by Microplanner Professional, five other commercial software packages and the optimal solution produced by Talbot's Optimiser.

The second was to produce a means to predict the performance of each software package given the type of network problem to be scheduled. The prediction tool was a multiple regression model for each of the software packages.

The third was a discussion of the practicality, or robustness, of optimally and heuristically produced schedules in the real world situation, such as a RAAF aircraft in DLM servicing. The task durations of a simple network were varied after its calculated schedule was commenced. The network was then dynamically rescheduled as the schedule progressed.

Optimal Solution Comparison

Procedure. Since the Microplanner X-Pert software was available only for a short time during the latter part of this research effort, it could not be fully evaluated. According to Micro Planning International, Microplanner's

X-Pert and Professional packages can be assumed to be computationally identical (16). The results from the Microplanner Professional software are therefore also used to assess the scheduling performance of Microplanner X-Pert.

The optimal solution comparison procedure consisted of taking a deterministic, resource constrained, network problem and comparing the resulting Total Duration for each software package with the Total Duration of the corresponding optimal solution, as shown in Figure 1.

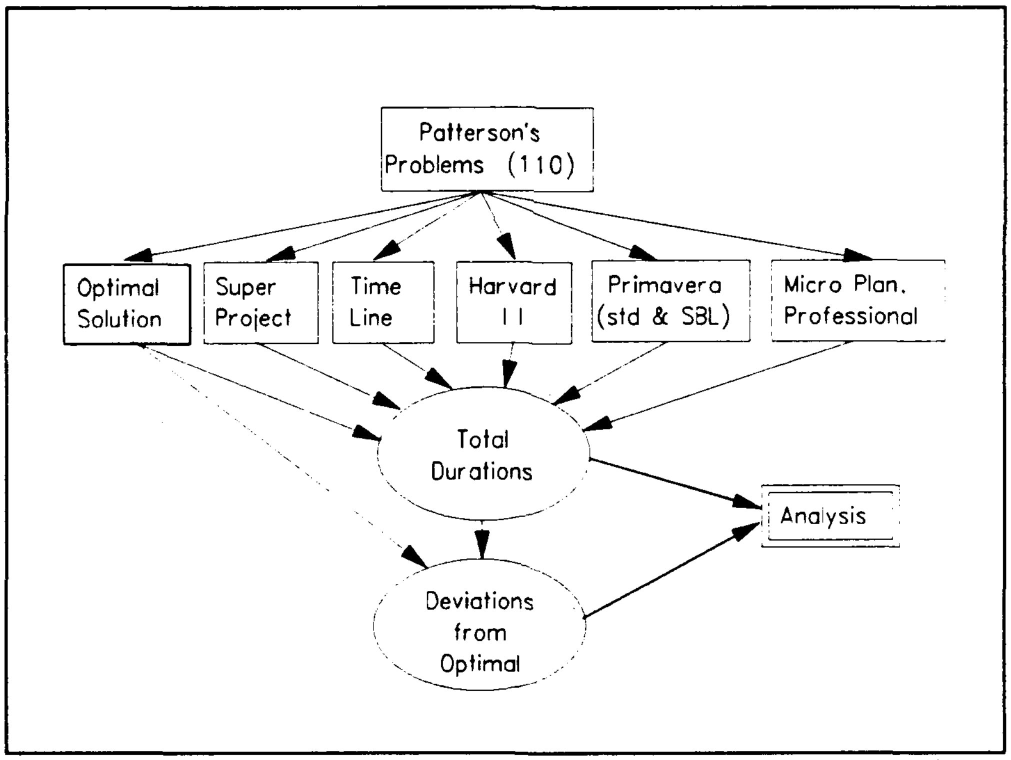

Figure 1. Schematic of Methodology for Comparative Analysis

In this paper, task schedules produced by Microplanner Professional and five other commercial software packages were compared against the optimal solution generated by Talbot's Optimiser. The comparison used the 110 problem set known as Patterson's problem set. Patterson's problem set was used because it is the closest to a standard network problem set identified in current literature.

The majority of the comparative data for the commercial software originated from an unpublished paper by Johnson (18). His paper produced Total Duration times for Super Project Expert 1.0, Timeline 2.0, Timeline 4.0, Harvard Total Project Manager II and Primavera 4.0, for each problem in Patterson's 110 problem set. In this paper, Johnson's work was extended by using Microplanner Professional to produce a task schedule and hence a Total Duration for each of Patterson's 110 problems.

Patterson's problem set was supplied for this research as an ASCII file by Simpson, who carried out work on the problem set during his doctoral research (33). Further details of the problem set are given in Appendix A.

It was necessary to convert Simpson's file information to a form compatible with the Microplanner Professional software. Simpson's ASCII data file was dissected into 110 individual data set files, one for each of Patterson's problems. Each of the files was reformatted into an ASCII format suitable for Microplanner Professional, imported into the Microplanner package and converted to a Microplanner project. The Microplanner software was then used to schedule each of the 110 problems, and the resulting Total

Duration for each of the problem sets was tabulated. Details of the data conversion and settings used in Microplanner Professional are given in Appendix B.

Validity Issues. Of practical necessity, the commercial software programmes considered for comparative testing did not include all of those currently available. The software selection for this paper was based on the selection made by Johnson (18). Each package selected is an established microcomputer-based project management system used in industry. Although not essential to the analysis of this paper, the assumption might reasonably be made that those selected are indicative of what is available to industry.

The scheduling performance of Microplanner Professional and Microplanner X-Pert could only be proved to be computationally identical if all 110 problems were run on both packages, and the results compared. However, Micro Planning International advised that the software is computationally identical, even though Professional is DOS based and X-Pert is Macintosh based (16). To give confidence to this declaration, a gross error check was conducted by solving three of Patterson's problem set with X-Pert, and comparing the results with Professional.

Patterson's problem set was assumed to represent the whole range of possible network types that the RAAF could use in aircraft DLM and other similar applications. The assumption is supported by the variety of problem sources, the significant number of problems (110 problems), and the range of the 58 network descriptive measures. Details of the 58 measures are shown in Appendix C.

However, the assumption cannot be rigorously verified on two accounts. First, insufficient data is currently available from the DLM facilities in the RAAF ASPS trial to conclude the nature of the network structures that will ultimately represent the DLM servicings. Second, Patterson's problem set is a collection of a broad range of networks collected from a number of notable published papers, rather than a purposely derived set of 110 diverse problems. The problems range in size from seven to 50 activities, with one to five logical successors for each activity and one to three resources consumed by each activity. No literature could be found which described the extent to which Patterson's problem set accurately represents the universal set of networks, particularly the larger networks such as may be found in large DLM servicing schedules.

The Total Duration results produced by Johnson were assumed to be subject to academic rigour and hence accurate. Johnson's results for the commercial software could not be validated without actually repeating his work. However, Johnson's results for Talbot's Optimal solutions were checked against Simpson's results.

Likewise, Simpson's ASCII data files were assumed to be an accurate transcription of Patterson's problem set.

Simpson advised that a series of validity checks were carried out on the data to ensure accuracy (34).

The accuracy of transformation of the ASCII data to the Microplanner Professional software was confirmed by randomly selecting ten problems of the set for checking. The checking procedure compared all the details of a network entered by keyboard to Microplanner with the details of imported ASCII data. This procedure also confirmed the internal consistency of the software package itself.

Data Analysis. The resulting Total Durations were examined using standard statistical techniques including means, standard deviations, and histograms.

Scheduler Performance Prediction Models

Procedure. The optimal solution comparison produced a data set containing Total Durations for each of the six software packages, for each one of Patterson's 110 problems. This Total Duration (TD) data set (6 x 110 elements) was then converted to a Deviation of Total Duration From Optimal (DOTDO) data set (6 x 110 elements) by subtracting the optimal Total Duration (1 x 110 elements) from each software package's Total Durations.

In a separate procedure, each of Patterson's problem networks was classified in terms of 58 network descriptive measures to yield a further data set, the Descriptive Measures (DM) data set (58 x 110 elements). The 58 network descriptive measures were chosen on the basis of their apparent usefulness as described in current literature. The values of these 58 measures were calculated for each of Patterson's 110 problems by reference to Simpson's work (33:202-217).

A stepwise multiple linear regression analysis was then run for the TD data set as a function of the DM data set. This produced seven regression models, one for each package and one for the optimal, with Total Duration as the dependent variable. The independent variables of the regression models were variously some of the 58 descriptive measures of the networks, as selected by the SAS stepwise regression programme. Each of the Total Duration regression models gave a prediction of that package's Total Duration based on the characteristics of the network problem to be solved.

Likewise, an additional six regression models were run to model the DOTDO data set as a function of the DM data set. These regression models gave a prediction of the deviation from optimal of each package's Total Duration time, based on the characteristics of the network problem to be solved.

The regression analysis was conducted by SAS (Version 6.06.01) using the "PROC REG STEPWISE" procedure with the "MAXR" option. The procedure, developed by James Goodnight (31:765), generated a linear multiple regression model with the highest possible model Coefficient of Determination (R^2) for a specified number of independent variables that were to be used in the model. As a starting point for this paper, models from one to 15 independent variables were generated using this procedure for each of the software packages. Larger models were not considered as they tended to include a number of independent variables of statistically marginal significance. Appendices D and E show the SAS programmes used to generate the models.

The 15 regression models, ranging from one to 15 variables for each software package, were examined to determine which were the most useful predictors. Model usefulness was assessed by the following factors:

a. low model Mean Squared Error (MSE) to enhance the precision of the model parameter and response estimates,

b. high model R^2 to account for as much of the data as possible,

c. low number of independent variables, to ensure model simplicity,

d. easily calculable independent variables, and

e. commonality of independent variables across all packages' models.

A schematic of the methodology for developing the prediction models is shown in Figure 2.

Use of the performance prediction models is not included in the scope of this paper due to the limitations of time and data. However, a suggested methodology for their use is included for completeness. Specifically, the two sets of resulting models, the Total Duration and the Total Duration Deviation From Optimal, must each be used in

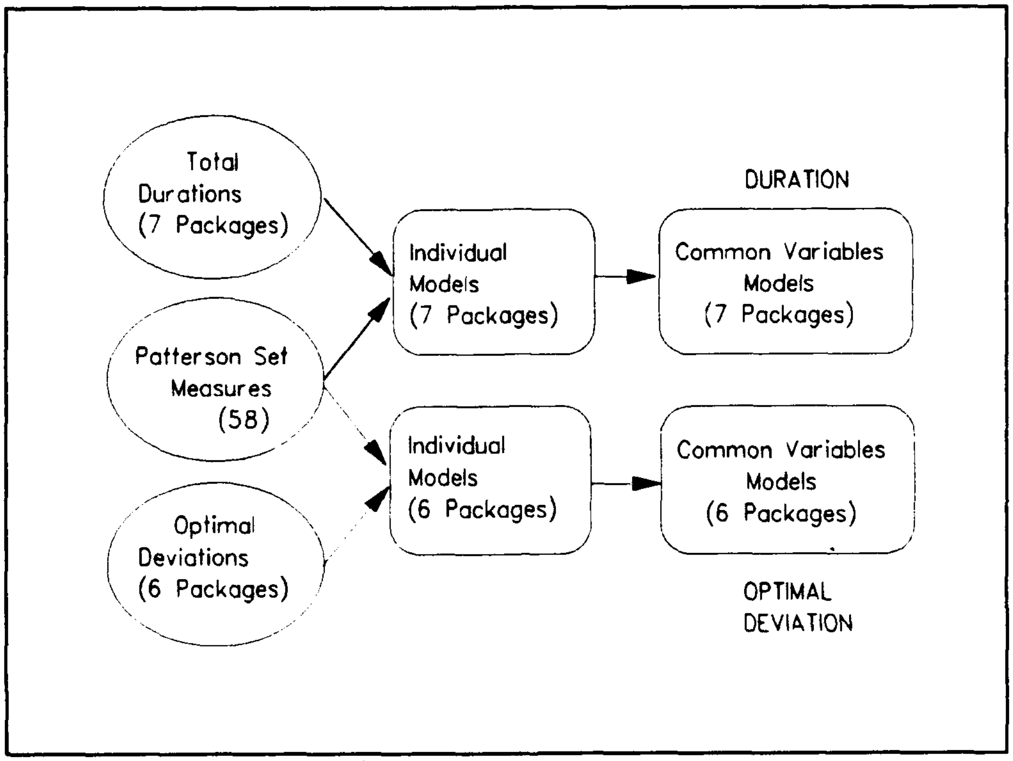

Figure 2. Schematic of Methodology for Performance Prediction Models

different ways to determine which software package will produce Total Durations closest to the optimal solution, for either the case of assessing an individual network or for assessing a group of networks.

When assessing an individual network using the Total Durations models then network measures are simply substituted into each software package's model and the results compared. The software package with the predicted value closest to the predicted optimal is considered the best package for that particular network, subject to the prediction model errors. The comparison takes the form of a series of hypothesis tests using a *t*-test as the test statistic. The hypothesis test to be performed on each software package is as follows:

$$H_o: \quad TD_p - TD_o = 0$$

where TD_p is the predicted Total Duration of a software package p and TD_o is the predicted Total Duration of the optimal solution package. This hypothesis test is applied to reject poorly performing packages rather than to find the best package because it is considered more important to mistakenly reject a good package than mistakenly accept a poor package. For this reason a low level of confidence, such as $\alpha=0.25$, can be chosen for the hypothesis test.

Similarly, when assessing an individual network using the Total Duration Deviation From Optimal models, the value of the network's measures are substituted into the model for each software package. The package with the smallest predicted value is the best package, subject to the prediction model errors. The hypothesis testing applied to each package's result is as follows:

$$H_o: \quad TDDO_p = 0$$

where $TDDO_p$ is the predicted Total Duration Deviation From Optimal for a package p. Again, the procedure is best used to eliminate poorly performing packages rather than finding the absolute best. A low level of confidence, such as $\alpha=0.25$, is also used in the hypothesis test.

The package yielding the closest to optimal on a number of networks can be assessed using the Total Duration models. The predicted values of Optimal Duration obtained from the models are subtracted from the values of Total Duration to yield values of deviation from optimal. These values are then analysed in the same manner as used in this paper for investigating the Optimal Solution Comparison. That is, the data is put into the form of cumulative frequency distributions to assess the package which most closely conforms to user's needs.

Similarly, the package which produces the closest to optimal for a number of networks can be found using the Total Duration Deviation From Optimal models. The predicted values of the network are again compared using the cumulative frequency distributions.

Validity Issues. The choice of the 58 descriptive measures was based on discussions of their usefulness indicated in current literature, although this tended to be somewhat arbitrary due to the large spectrum of measures considered in this paper. Initial inclusion of so many measures was not of great concern for the model performance as the stepwise regression procedure simply discards those which do not contribute significantly to the model's R^2 value. However, the procedure may discard variables which have potential value in meeting other criteria of usefulness detailed previously, such as commonality of variables across a number of models. One condition that may result in the unwanted deletion of certain variables is multicollinearity, which occurs "when one of the X variables can be expressed as a linear combination of other X variables" (10:407). Therefore, the existence of multi-collinearity was also checked to ensure that potentially useful variables were not hidden. The collinearity was calculated using the SAS procedure "PROC REG" with the "VIF" (Variance Inflation Factor) option (31:660). The VIF is simply:

$$VIF = \frac{1}{(1-r^2)} \tag{1}$$

where r is the multiple correlation coefficient (10:408). When r is at its minimum value of zero then the VIF is 1.0. As r approaches its maximum value of 1.0 then the VIF increases without bound.

To confirm model aptness, the residuals of potentially suitable models were plotted versus their estimated response, and then analysed. The analysis considered the randomness of the plotted points and the number of points lying beyond two standard deviations. The SAS "PLOT RESIDUAL" option in "PROC REG" was used to produce the residuals. Further analysis of the residuals by testing their frequency distribution for normality was not included.

Further validation may be carried out by inserting data from new problems into the models and testing the significance of the differences between actual and predicted Total Durations. As access to the majority of the software packages was not available for this paper, this procedure was not included.

Data Analysis. Standard linear regression techniques were used to assess the regression data. For this paper, the level of confidence required for the model's F-statistics was set at 0.05, that is, the probability of making a Type 1 error must be less than 0.05 in all cases. Levels of R^2 required were set to be a minimum of 0.90, and the VIF value was considered acceptably low at less than 3.0.

Optimal Solution Robustness in the Dynamic Environment

Procedure. Schonberger's paper (32) and Goldratt and Cox's book (14) alluded to problems with the robustness of deterministic solutions in the dynamic environment of industry. However, they did not provide a suitable methodology to illustrate quantitatively these fundamental difficulties for CPA. This paper has endeavoured to outline a possible means using a single network with multiple constrained-resources. However, due to time limitations, only a rudimentary discussion has been put forward. The basis of the methodology was to illustrate how useful, or robust, the optimal and heuristic deterministic CPA solution techniques are under conditions of task duration variability.

In the case of static scheduling, the estimated Total Duration usually understates the actual project duration if the task duration times on the critical path vary. Additionally, if task duration times on near critical paths vary they may also cause an understatement of the actual project duration. A potential improvement in minimising the Total Duration whilst matching the scheduled project duration with the actual project duration is the use of dynamic rescheduling, that is, rescheduling the project after the schedule commences when estimates of task durations change. Intuitively, dynamic rescheduling should be more accurate than static CPA scheduling under conditions of task duration variability. Further, dynamic rescheduling using an optimal technique should be more accurate than that using an heuristic scheduling technique. To investigate these issues, a simple network, problem number two, was arbitrarily chosen from Patterson's problem set. Figure 3 and Table 2 describe Patterson's problem number two.

The problem two network was first scheduled normally in two ways, using Microplanner Professional and Talbot's Optimiser. The scheduling was exactly the same as that discussed in the previous sections of this paper, that is, static scheduling of a resource-constrained single project network. The resulting Total Durations were noted.

To provide a more realistic representation of the actual project scheduling problem in industry, such as RAAF aircraft DLM, simulations were then conducted with variability incorporated into all task durations of problem number two. As each task commenced, its estimated duration was changed. Assuming task independence, the new task duration was determined by randomly selecting a value from a uniform distribution that had a mean equal to the original task duration and a specified percentage range of

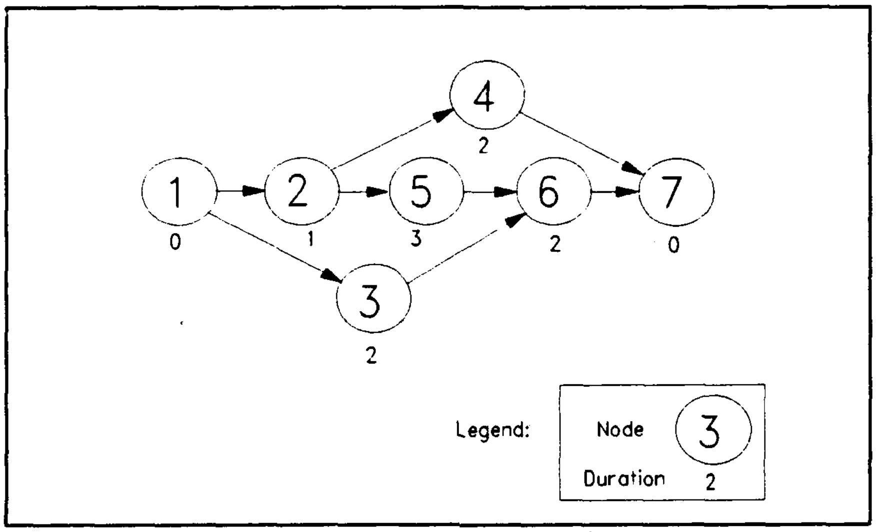

Figure 3. Network Representation of Patterson's Problem Number Two

TABLE 2

PATTERSON'S PROBLEM NUMBER TWO

ACTIVITY NUMBER	DURATION	SUCCESSOR ACTIVITY NUMBERS	RESOURCE USAGES TYPE 1	TYPE 2	TYPE 3
1	0	2, 3	0	0	0
2	1	4, 5	2	2	1
3	2	6	0	2	1
4	2	7	3	3	3
5	3	6	2	1	3
6	2	7	1	1	0
7	0	-	0	0	0
		Availability Limits:	5	5	3

variability. That is, for a variability of plus or minus 5% then the task duration was uniformly distributed between 0.95 to 1.05 times the static task duration. The project schedule was then recalculated using the newly selected task duration. The procedure was subsequently repeated for all tasks until the end of the project. Simulation of the network's dynamic scheduling was carried out 1000 times for each of six sets of random variations: plus or minus 5%, 15%, 25%, 35%, 50% and 75% of the original task durations. To increase the validity of comparisons, the random number streams were synchronised. That is, the same streams were used for each 1000 replication block. To maintain simplicity in the analysis, resource consumption rates and supply rates were not varied throughout the project.

The general methodology proposed in Figure 4 includes an investigation of the differences between dynamic scheduling with heuristic techniques and optimal techniques. For example, investigation of the performance differences could be achieved if Microplanner Professional were to be used for one series of 5%, 15%, 25%, 35%, 50% and 75% variability, followed by use of Talbot's Optimiser for a second series, as shown in Table 3. However, in the case of problem two, dynamic rescheduling did not alter the schedule's task sequence due to the problem's particular precedence and resource constraints. Therefore, the simulations for problem number two were generated

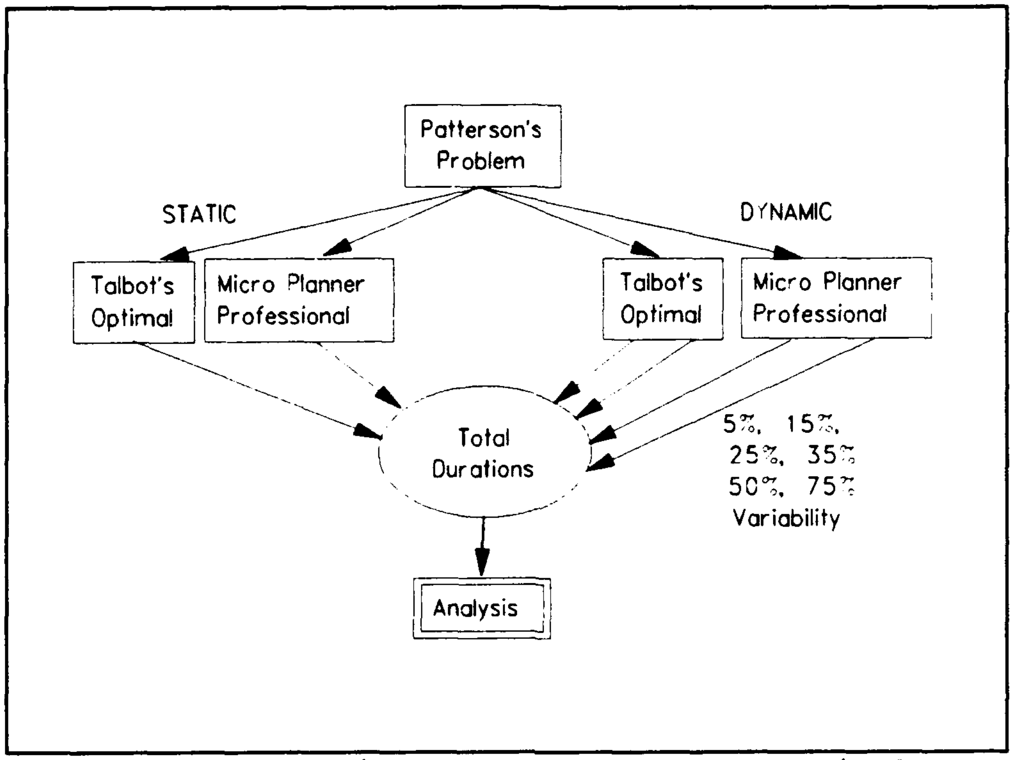

Figure 4. Schematic of Methodology for Optimal Solution Robustness in the Dynamic Environment

TABLE 3

DESIGN OF DYNAMIC SCHEDULING TRIALS

SCHEDULING TECHNIQUE	DEVIATION LEVEL	REPLICATIONS
Microplanner Professional	5%	1000
	15%	1000
	25%	1000
	35%	1000
	50%	1000
	75%	1000
Talbot's Optimiser	5%	1000
	15%	1000
	25%	1000
	35%	1000
	50%	1000
	75%	1000

equivalently, yet more simply, on a Quattro Pro 3.0 spreadsheet by considering the Total Duration as the sum of the following durations: the maximum of tasks two and three, task five, and the maximum of tasks four and six. This can be seen by considering the optimal static schedule for problem two, shown in Figure 5.

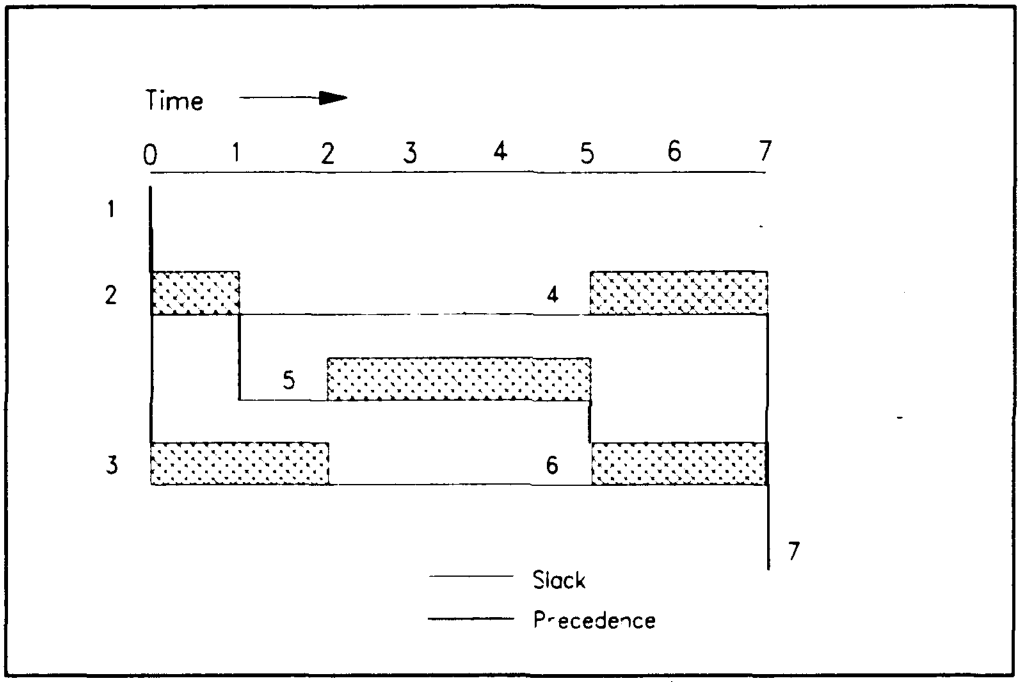

Figure 5. Optimal Solution to Patterson's Problem Number Two

Validity Issues. The methodology put forward in Figure 3 considers four basic project network scheduling techniques: static heuristic, static optimal, dynamic heuristic and dynamic optimal. There are potentially others which may be considered but they have not been included in this discussion.

The assumption that all tasks varying according to a uniform distribution with particular upper and lower limits was arbitrary for the purposes of this discussion. The essential requirement was that some known variability was introduced to task durations. However, using the uniform was a conservative choice. The commonly accepted distribution for task durations is unimodal Beta which has tapered tails and a right skew, thus biasing tasks to have longer overruns than underruns.

In simulation of the dynamic scheduling, the assumption was made that the task durations were known before rescheduling. This may or may not occur in practice in industry, but the assumption does not materially affect the intent of this investigation.

The choice of problem two precludes the full analysis shown in Figure 3 where dynamic scheduling for optimal and heuristic techniques are expected to produce different results. However, problem two is sufficient to illustrate the basic issue of how variability in task durations affects the Total Duration.

The validity of using the spreadsheet to simulate the dynamic rescheduling of problem number two can be confirmed by realising that the precedent and resource constraints of its network prevent the tasks from changing their sequences for any changes in task durations. However, for completeness, several examples were calculated by Microplanner

Professional, Talbot's Optimiser and spreadsheet to confirm the assumption.

Synchronisation of the random number streams adds to validity of the simulation because each simulation uses the same set of random numbers for all levels of task duration variability. The results for the 5%, 15%, 25%, 35%, 50% and 75% levels of variability can be therefore directly compared without needing to account for any differences introduced by using different sections of one long random number stream.

Data Analysis. The Total Durations of the static and dynamic schedules were compared, using basic statistical techniques.

IV. Experimental Results and Data Analysis

This chapter presents the results of the procedures and validity checks described in the Methodology section, Chapter III. The results are presented in the order outlined in Chapter III.

Optimal Solution Comparison

Validity Checks. All validity checks were successfully carried out. There were three anomalies detected.

First, the ASCII data set from Simpson was marginally different to that used by Johnson. In Patterson's problem 13, Simpson converted the zero duration activities which consumed resources to show a duration of one. Simpson advises (34) that this was done to enable Talbot's Optimiser to function properly. The reason for Patterson's inclusion of resource consumptions for a zero duration activity is unclear. As resource consumption is expressed in units of resources consumed per unit time, a consumption rate for a zero duration is apparently meaningless. Simpson's figures were used in this paper because Microplanner Professional, like Talbot's Optimiser, would not accept resource consumption for a zero duration activity.

Second, Johnson's paper showed a minor internal inconsistency in the summation of the Super Project Total Duration. The total should be 4117 rather than 4118.

Third, Johnson's paper stated that the Total Duration of Talbot's Optimal solution for problem 105 was 77, whereas Simpson calculated this to be 76. The value of 76 is used in this paper.

Results. A summary of Total Durations from Johnson's paper, including the above amendments and the results from Microplanner Professional, is tabulated in Appendix F. Johnson compared the summation of Total Durations over all the 110 problems and then related them to the optimal results. This gave an average performance of the schedulers over all 110 problems. A summary of the Appendix F results using Johnson's analysis procedure is given in Table 4.

TABLE 4

SUMMARY OF TOTAL DURATION RESULTS

SCHEDULING PACKAGE	TOTAL OF DURATIONS	PERCENT INCREASE OVER OPTIMAL
Talbot's Optimiser	3835	0
Super Project	4117	7.35
Timeline	4029	5.06
Harvard	4219	10.01
Primavera	4184	9.10
Primavera (SBL)	4382	14.26
Microplanner Professional	4141	7.98

However, Johnson's analysis failed to show the distribution of each package's performance over the 110 problems. For example, one package may achieve the optimal Total Duration on 100 of the 110 problems and be 20% different for the other 10 problems. If that 20% were for problems of relatively short Total Duration, then the package would show very well in Johnson's analysis. But, if that 20% were for problems of longer Total Duration, then Johnson's analysis would show the package as a poor performer.

This paper has considered the performance measure of a scheduler to be the percentage difference of Total Duration from optimal on each of the problems, rather than the summation of differences over all 110 problems. Therefore, the mean and standard deviations of the performance percentages were taken to comment on the ability of each software package to produce closely optimal and consistent results. The results of percentage calculations for all 110 problems are shown in Appendix G. A summary of these results is given in Table 5.

The averages of percentage deviations found in Table 5 are only marginally different from the overall percentage deviations found by Johnson's method in Table 4. However, the Table 5 standard deviation results highlight the inconsistency of performances by all commercial packages. The package with the smallest average percent deviation and variability is Timeline, with an average of 5.2%, followed by Super Project and Microplanner Professional. The results of Primavera with the SBL option were generally so poor that they will be omitted from further discussion.

The Appendix G results also show that for individual problems there is often a high variability in Total Duration

TABLE 5

SUMMARY OF OPTIMAL DEVIATION RESULTS

SCHEDULING PACKAGE	AVERAGE OF PERCENT DEVIATION	STANDARD DEVIATION OF PERCENT DEVIATION
Talbot's Optimiser	0	0
Super Project	7.1	6.5
Timeline	5.2	5.6
Harvard	10.4	9.4
Primavera	9.9	7.4
Primavera (SBL)	14.1	11.9
Microplanner Professional	7.7	7.9

performances across the five software packages. For example, in problem seven, three of the packages had 0% deviation from optimal whereas the other two deviated by 38% from optimal.

However, reference to averages and standard deviations does not adequately describe the distribution of performance results. Therefore, the information in Appendix G is collated as class frequency histograms and presented in

Figures 6 to 11. The x-axis labels of these figures are the upper values of each frequency class. For example, the bar labelled "10" represents the number of Patterson's problems where the software produced Total Durations that were more than 5% but less than or equal to 10% above the optimal value. The bar labelled "0" represents those times that the scheduler produced Total Durations equal to the optimal.

Cumulative relative frequency distributions are also calculated, as shown in Figures 12 to 17. They show clearly the proportion of times that the packages are able to achieve Total Durations within a nominated percentage of optimal. As Davis and Patterson (6:951) reported that good heuristics tend to fall within five to ten percent of optimal, the 0% to 10% relative frequency values are highlighted in Figures 9 to 14, and summarised in Table 6.

The 0% to 15% and 0% to 20% ranges are also summarised in Table 6 to illustrate the significant differences in performances. Timeline has 0.95 of its Total Durations within 15% of optimal whereas Harvard has only 0.72 within 15%. The results in Table 6 confirm the earlier results that Timeline is the best performing package, followed by Super Project and Microplanner Professional.

Although this analysis has identified, on average, the relative ranking of each software package's scheduling performances, the performance of a software package for a particular network or class of networks cannot be determined from this analysis.

TABLE 6

SUMMARY OF CUMULATIVE OPTIMAL DEVIATION RESULTS

SCHEDULING PACKAGE	CUMULATIVE RELATIVE FREQUENCY OF PERCENT DEVIATION FROM OPTIMAL		
	0%-10%	0%-15%	0%-20%
Talbot's Optimiser	0	0	0
Super Project	0.74	0.91	0.96
Timeline	0.86	0.95	0.98
Harvard	0.58	0.72	0.84
Primavera	0.55	0.79	0.94
Primavera (SBL)	0.45	0.55	0.77
Microplanner Professional	0.67	0.83	0.92

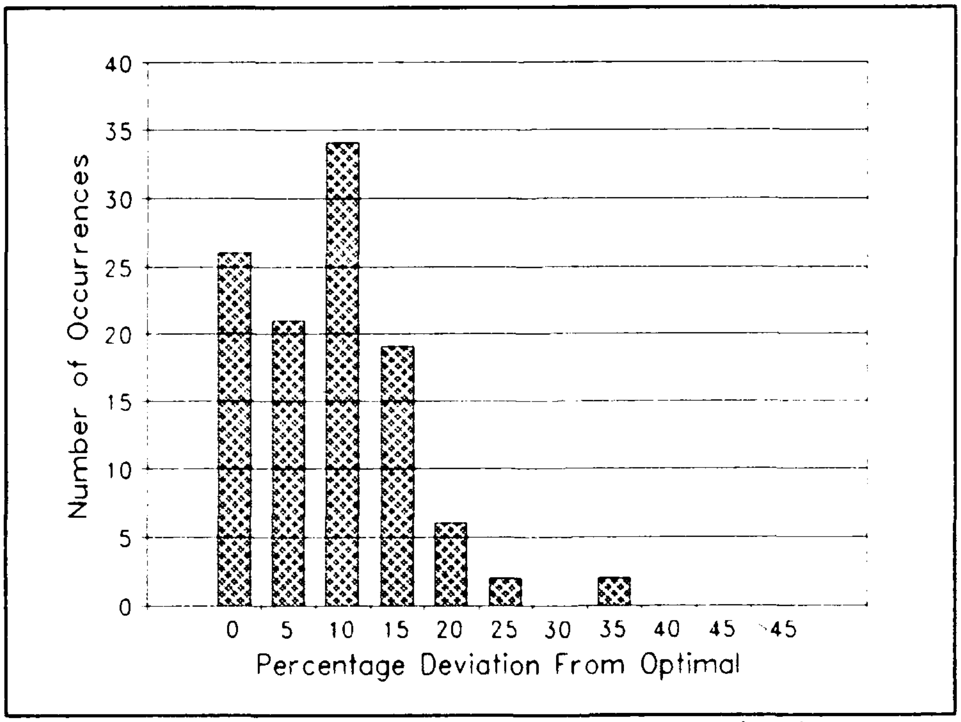

Figure 6. Super Project's Percent Deviation From Optimal

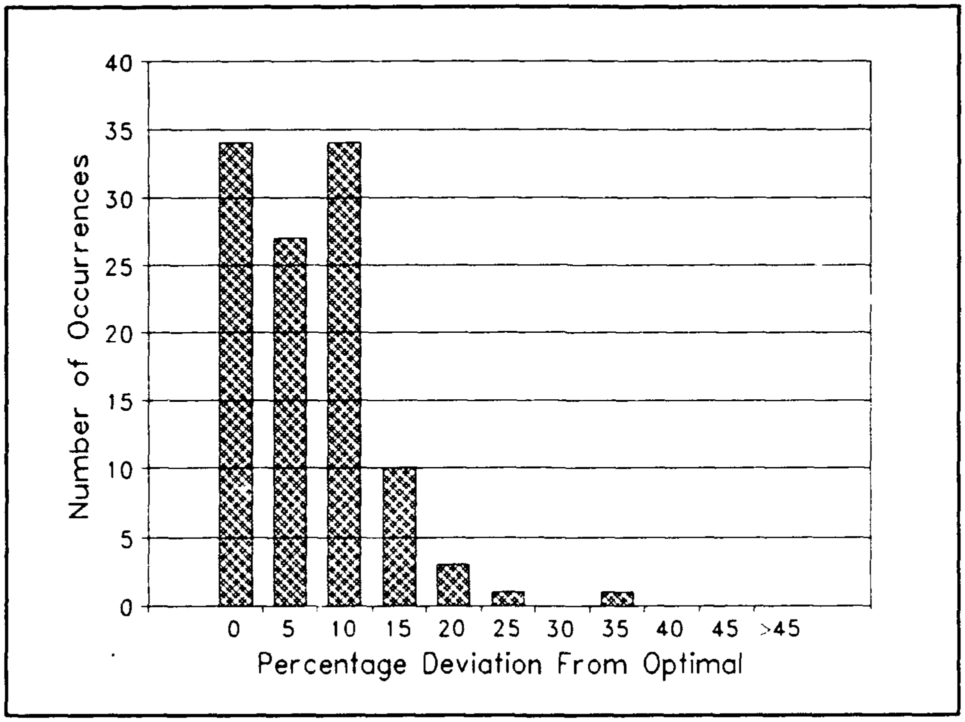

Figure 7. Timeline's Percent Deviation From Optimal

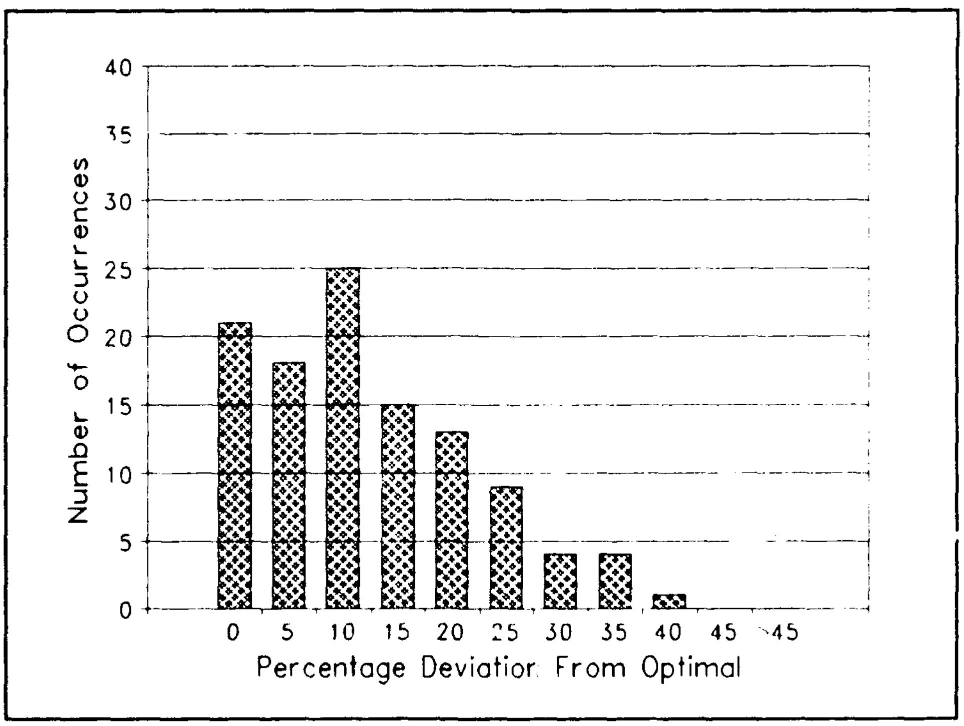

Figure 8. Harvard Project Manager II's Percent Deviation From Optimal

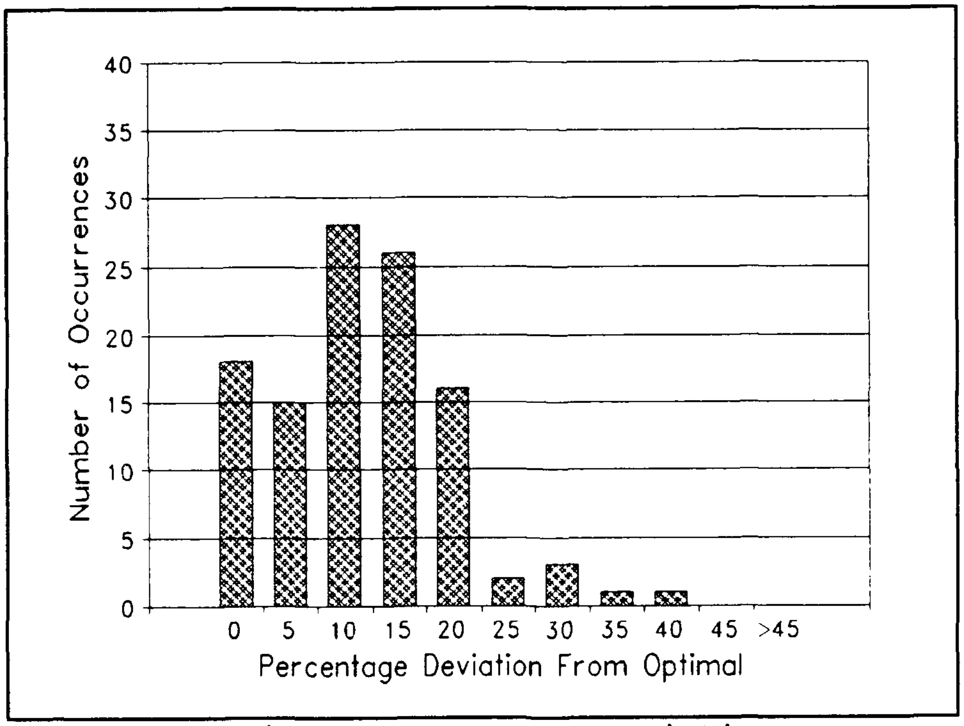

Figure 9. Primavera's Percent Deviation From Optimal

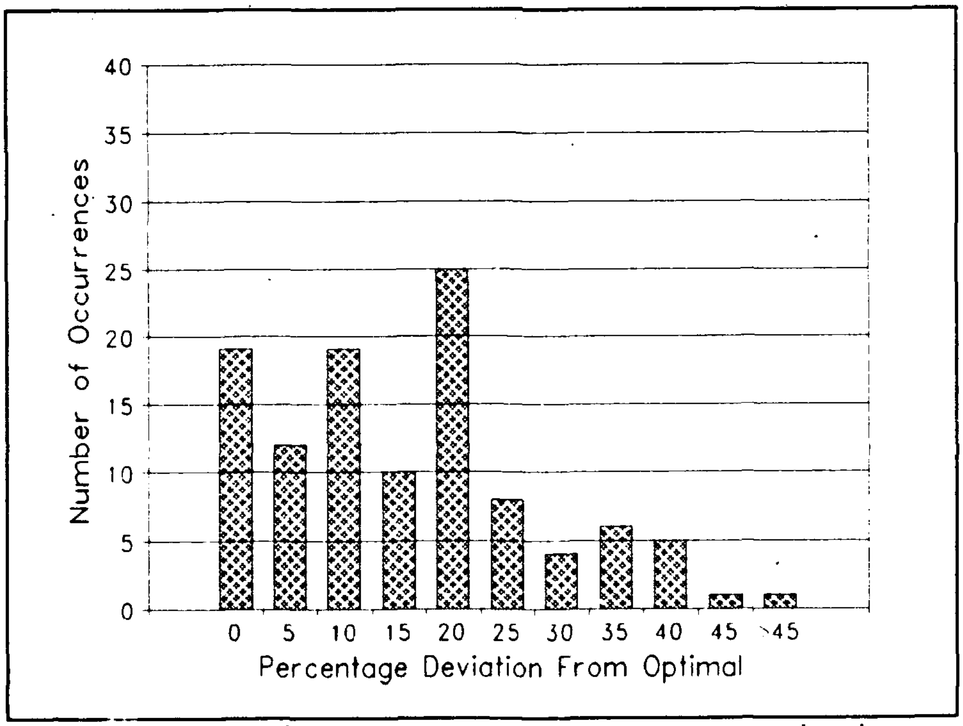

Figure 10. Primavera (SBL)'s Percent Deviation From Optimal

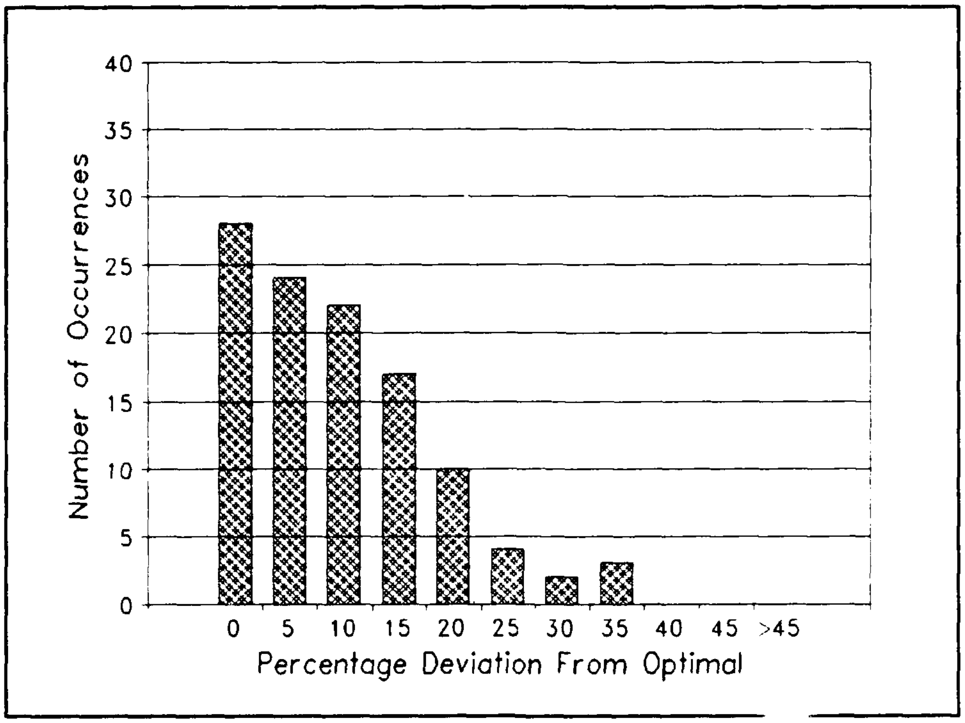

Figure 11. Microplanner Professional's Percent Deviation From Optimal

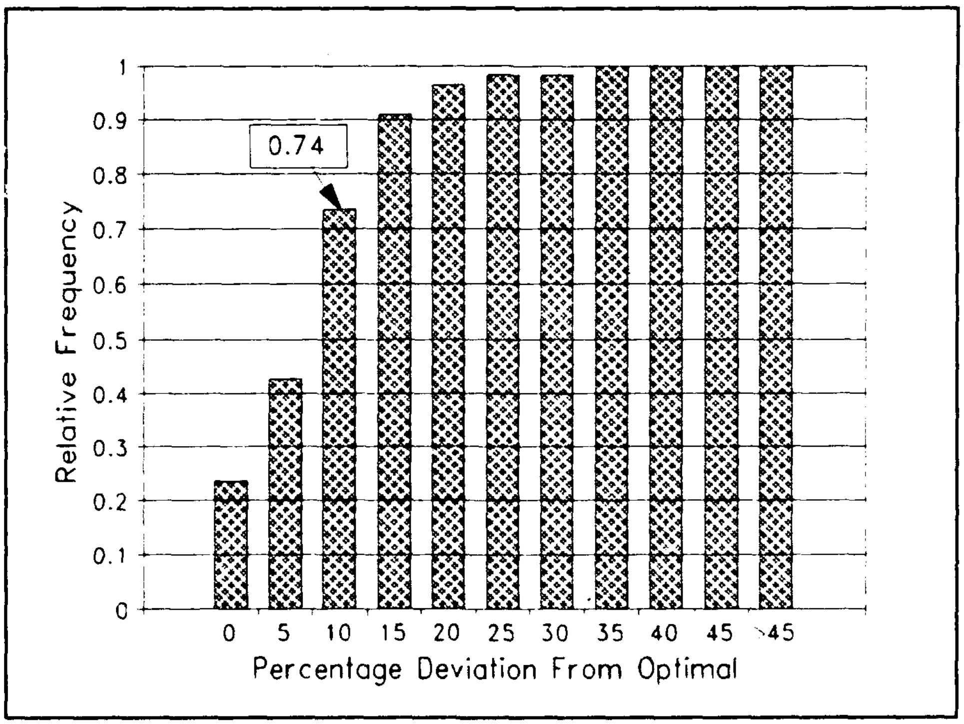

Figure 12. Super Project's Percent Deviation From Optimal--Cumulative Relative Frequency

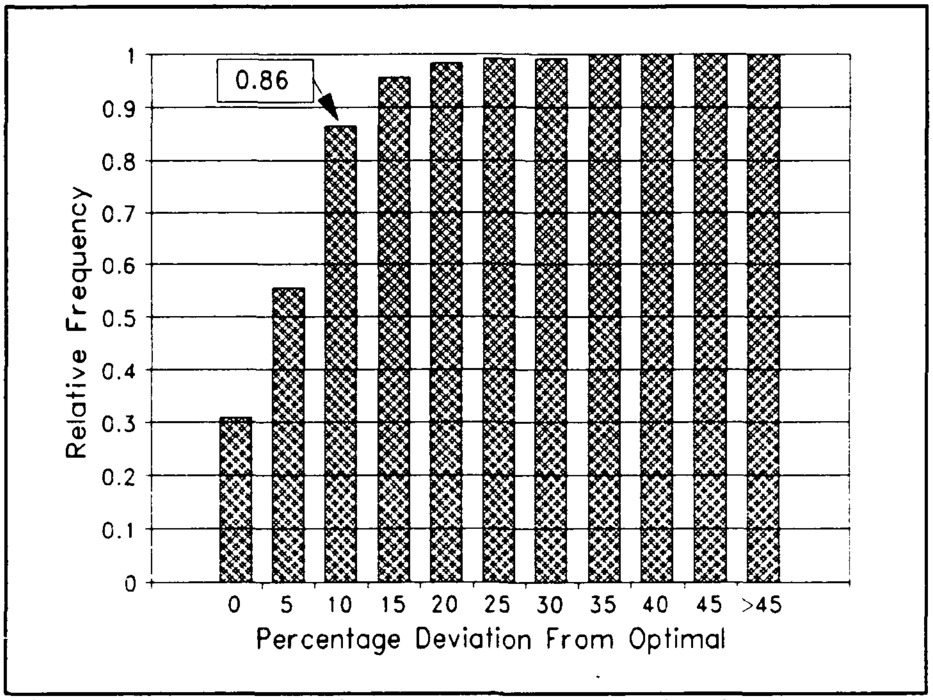

Figure 13. Timeline's Percent Deviation From Optimal--Cumulative Relative Frequency

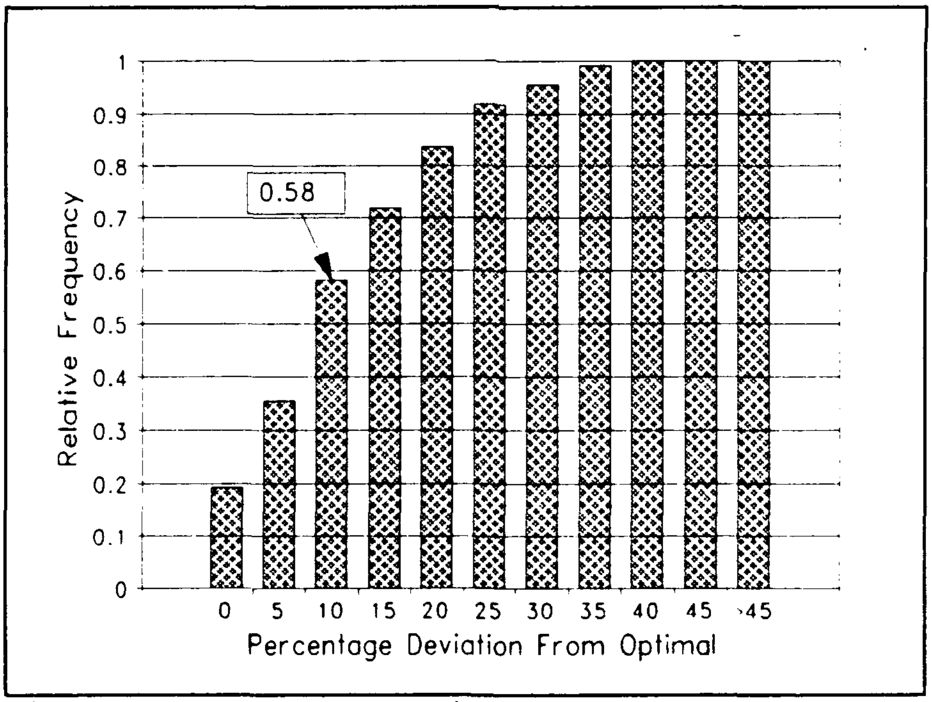

Figure 14. Harvard Project Manager II's Percent Deviation From Optimal--Cumulative Relative Frequency

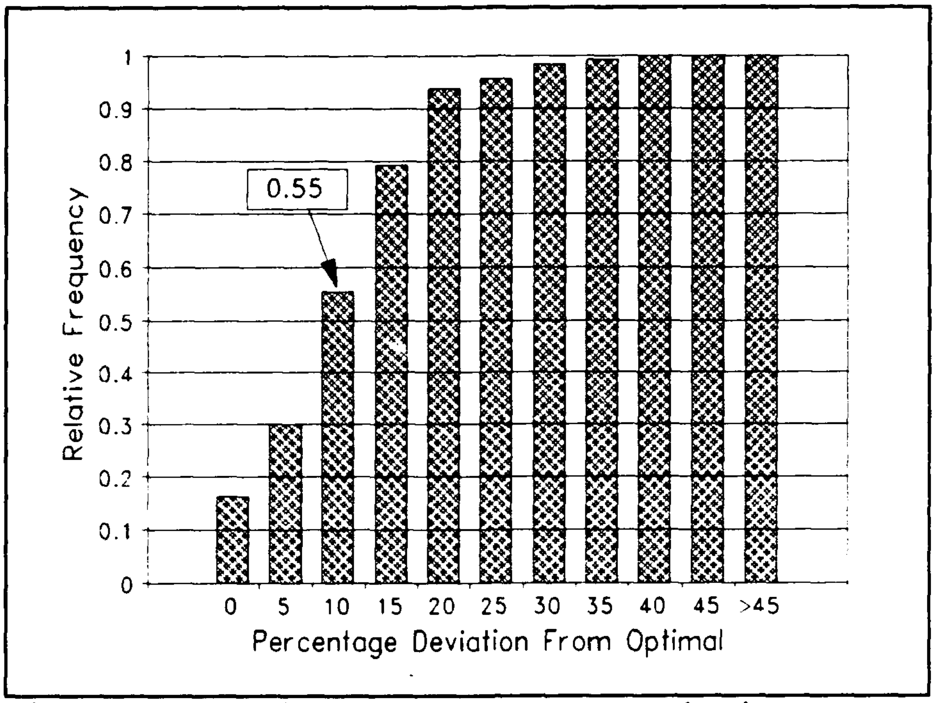

Figure 15. Primavera's Percent Deviation From Optimal--Cumulative Relative Frequency

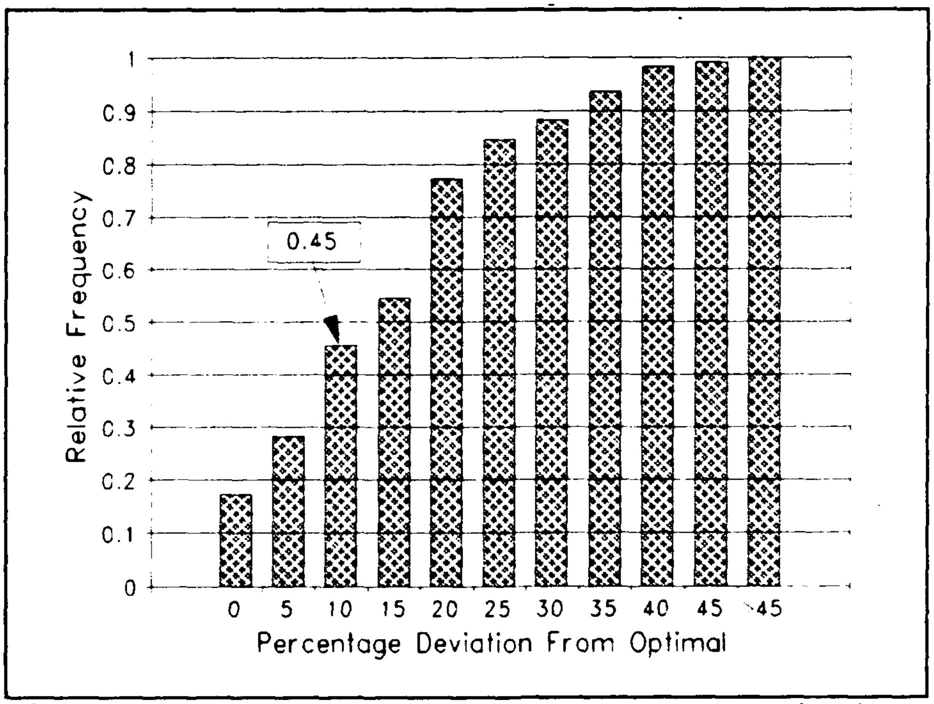

Figure 16. Primavera (SBL)'s Percent Deviation From Optimal--Cumulative Relative Frequency

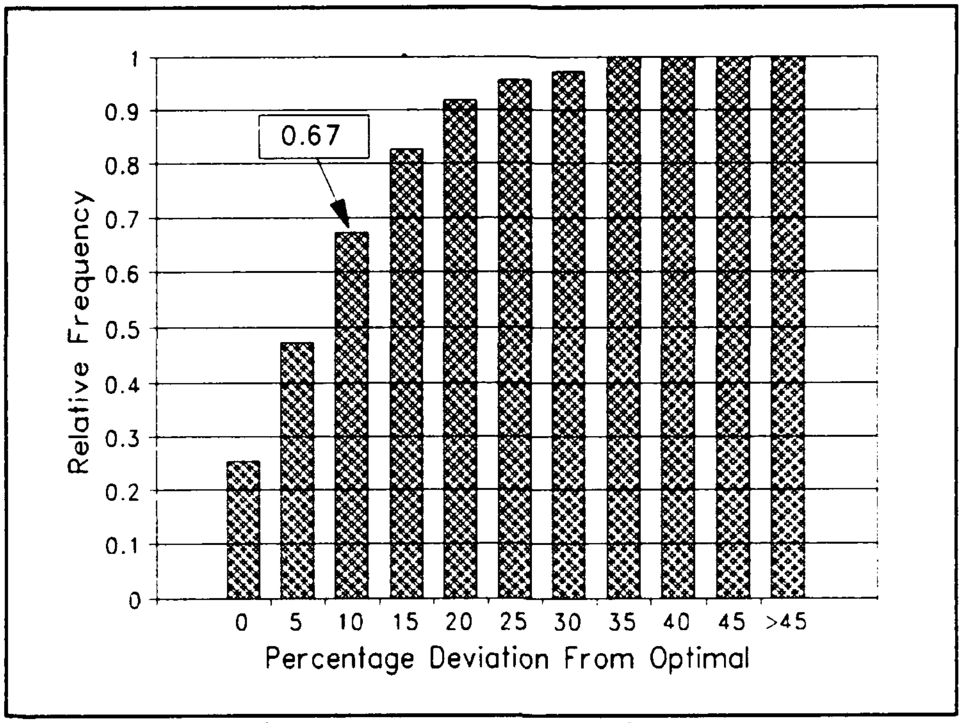

Figure 17. Microplanner Professional's Percent Deviation From Optimal--Cumulative Relative Frequency

Scheduler Performance Prediction Models

Total Duration Models. Fifteen possible Total Duration models were produced for each of the six software packages with the SAS stepwise regression procedure. The models were based on the TD data set as a function of the DM data set. All of the possible models had high R^2 values with many having common variables across software packages.

Table 7 summaries the models' R^2 results for each software package. The dashed entries indicate the models that had at least one independent variable with a *p*-value greater that 0.1 for the *t* statistic testing H_o: $\beta_i=0$, where β_i is the model's coefficient of that independent variable.

Those models have been excluded from consideration to ensure that there is a high confidence that all model independent variables contribute significantly to the model. The results show that, with the exception of Primavera (SBL), all models from two to ten variables have R^2 greater than 0.9 and F-Statistic *p*-value less than 0.1.

TABLE 7

SUMMARY OF SAS "PROC STEPWISE" R^2 RESULTS
FOR TOTAL DURATION MODELS

SCHEDULING PACKAGE	R^2 WITH NUMBER OF VARIABLES IN MODEL						
	1	2	3	4	5	10	15
Talbot's Optimiser	.84	.94	.95	.97	.97	.99	.99
Super Project	.78	.91	.93	.94	.95	.97	-
Timeline	.80	.93	.94	.96	.96	.98	.99
Harvard	.79	.92	.93	.94	.94	.96	.97
Primavera	.80	.93	.95	.96	.96	.98	-
Primavera (SBL)	.78	.89	.92	.93	.93	.95	-
Microplanner Professional	.77	.91	.93	.94	.96	-	.98

The extent of commonality of the regression models' independent variables was examined by tabulating the variables against their occurrence in the regression models. This tabulation, in matrix form, is included as Appendix H. The matrix shows that all the one and two variable models have common variables. Also, with the exception of

Primavera (SBL) and one variable in the Talbot's Optimiser model, the three variable model had common variables. Models with more than three variables tended to have fewer common variables.

The VIF analysis of the models showed that all the two and three variable models exhibited acceptable collinearity levels, that is, less than 3.0. However, for more than three variables some of the models showed unacceptably high values, that is, greater than 5.0. The VIFs for the one variable models are not calculated because, by definition, the VIF of a one variable model equals 1.0. VIF values are shown in Table 8.

TABLE 8

SUMMARY OF SAS "PROC STEPWISE" MAXIMUM VIF VALUES FOR TOTAL DURATION MODELS

SCHEDULING PACKAGE	VIF WITH NUMBER OF VARIABLES IN MODEL				
	2	3	4	5	10
Talbot's Optimiser	1.0	1.0	2.8	2.6	40.0
Super Project	1.0	1.3	9.9	18.4	7.7
Timeline	1.0	1.4	8.9	10.2	28.9
Harvard	1.0	1.3	3.4	10.0	12.1
Primavera	1.0	1.3	9.9	18.4	24.8
Primavera (SBL)	1.0	2.4	3.0	2.7	14.7
Microplanner Professional	1.0	1.3	2.1	4.6	9.5

Plots of the residuals versus the dependent variable, Total Duration, showed that for the one, two and three variable cases, the models were generally satisfactory. The plot values were well scattered, with very few outliers.

Total Duration Deviation From Optimal Models. Fifteen possible models were produced by the SAS stepwise regression procedure for each of the five commercial software packages to predict the Total Duration From Optimal. The models were produced by considering the DOTDO data set as a function of the DM data set. The resulting models showed low R^2 values and few variables in common across the software packages.

All R^2 values of the models were considerably lower than the threshold of 0.9 set in this paper, as can be seen in Table 9. As before, the dashed entries indicate models with variables having an F-statistic *p*-value greater than 0.1.

The commonality of independent variables across the models is tabulated in matrix form at Appendix I. There are no variables in common across all packages, and few in common between groups of packages.

VIF values for the models one, two, three four and five variables were calculated in SAS, and summarised in Table 10. The VIF values were generally low, indicating that other independent variables could not be substituted into the models to improve commonality across packages.

Plots of residuals versus the dependent variable, Total Duration Deviation From the Optimal, all showed that the

TABLE 9

SUMMARY OF SAS "PROC STEPWISE" R^2 RESULTS
FOR TOTAL DURATION DEVIATION FROM OPTIMAL MODELS

SCHEDULING PACKAGE	R^2 WITH NUMBER OF VARIABLES IN MODEL						
	1	2	3	4	5	10	15
Super Project	.28	.35	.40	.44	-	-	-
Timeline	.30	.34	.38	.40	.43	-	.57
Harvard	.15	.22	.24	.28	.30	.38	-
Primavera	.26	.38	.46	.52	.55	-	.67
Primavera (SBL)	.13	.17	.22	.25	.27	.45	-
Microplanner Professional	.20	.30	.36	.38	.39	-	-

TABLE 10

SUMMARY OF SAS "PROC STEPWISE" MAXIMUM VIF VALUES
FOR TOTAL DURATION DEVIATION FROM OPTIMAL MODELS

SCHEDULING PACKAGE	VIF WITH NUMBER OF VARIABLES IN MODEL			
	2	3	4	5
Super Project	1.2	1.6	1.7	1.7
Timeline	1.0	1.1	5.0	2.9
Harvard	1.0	1.7	2.0	1.2
Primavera	1.0	1.1	2.6	2.6
Primavera (SBL)	1.0	1.6	2.2	2.9
Microplanner Professional	1.1	4.9	5.5	6.1

residuals clustered along a positively sloped straight line. The current models therefore require additional terms that were not considered in the network measures.

Optimal Solution Robustness in the Dynamic Environment

Static Scheduling. The results of scheduling problem two with Microplanner Professional and Talbot's Optimiser are identical. The Total Duration is seven time units, as shown in Figure 5.

Dynamic Scheduling. Use of the Quattro Pro spreadsheet to produce simulations of task variabilities was checked by solving problem two for five different task durations with Microplanner Professional, Talbot's Optimiser and the spreadsheet. As asserted in Chapter III, the results were identical, due to the nature of problem number two. Whilst performing these checks it was found that both Microplanner Professional and Talbot's Optimiser would accept only integer values of task durations. Therefore, to carry out these simulations the actual task durations were multiplied by 1000 for input to the schedulers with the resulting Total Durations then being divided by 1000.

For each calculative iteration, the spreadsheet produced 1000 replications of the problem two network for each of the six levels of task duration variability. Using this approach, five separate random number streams were run in parallel to achieve simulation synchronisation.

The results of the simulations are shown in Table 11. This table shows that, on average, the network path length

TABLE 11

SUMMARY OF SIMULATION RESULTS FOR UNIFORMLY DISTRIBUTED TASK VARIABILITIES OF PATTERSON'S PROBLEM NUMBER TWO (1000 REPLICATIONS)

MEASURE	PERCENT TOTAL DURATION ABOVE OPTIMAL GIVEN VARIABILITY LEVELS OF TASK DURATIONS					
Variability	5%	15%	25%	35%	50%	75%
Average Total Duration	0.58	1.75	2.92	4.09	5.97	9.55
Minimum Total Duration	-3.77	-11.3	-18.84	-26.38	-37.28	-55.11
Maximum Total Duration	4.71	14.13	23.56	32.98	47.12	70.67

or Total Duration, was always longer than the optimal (deterministic) Total Duration. A frequency distribution of the Table 11 results is shown in Figure 18. Accounting for scaling, each level of variability had an identical distribution shape due to synchronisation of the simulation. But, all distributions were displaced and skewed right due to the cumulative effects of summing durations of the longest tasks in the network. Therefore, despite the symmetrical distribution given to the task durations, the Total Duration was more likely to be longer than the optimal Total Duration.

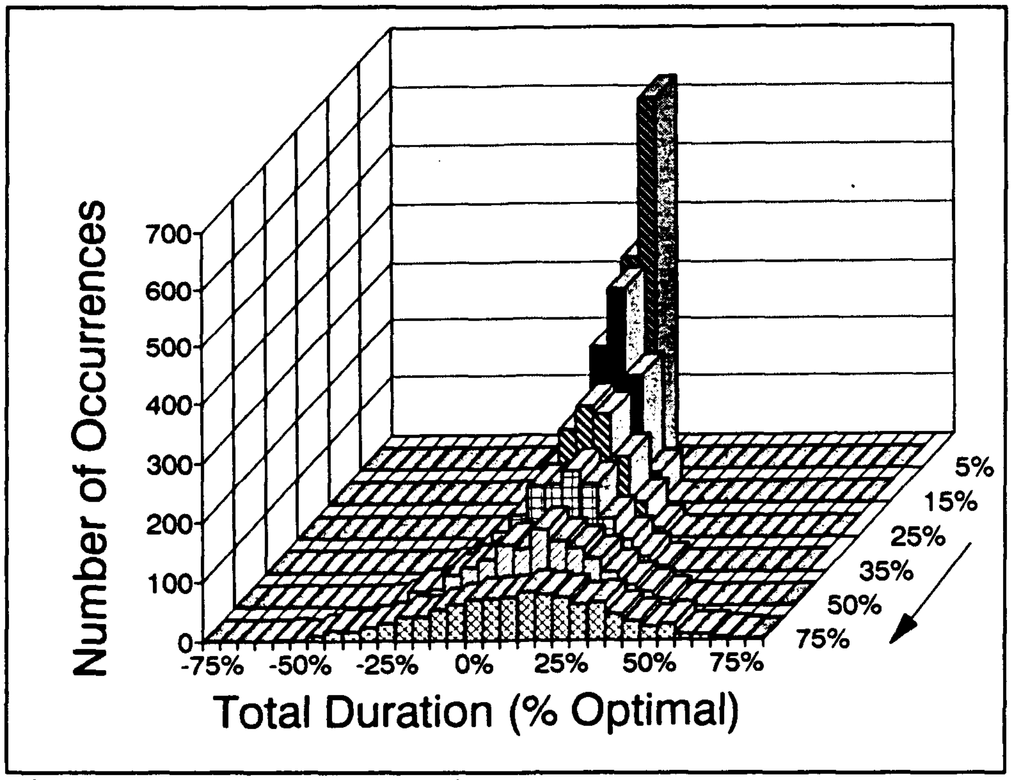

Figure 18. Total Durations For Patterson's Problem Two With Uniform Distribution Task Variabilities

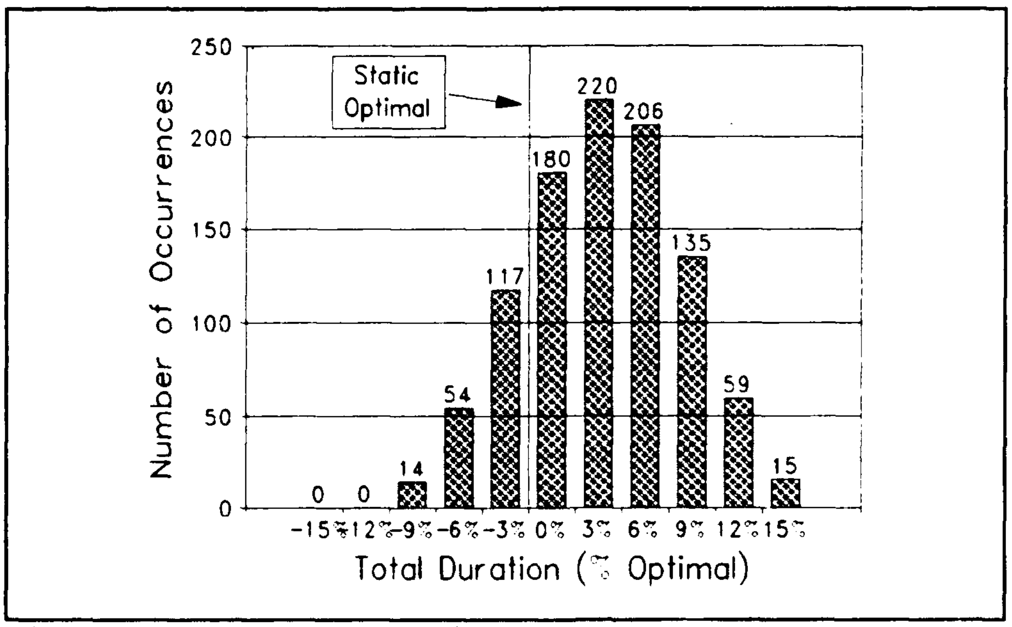

Figure 19. Total Durations for Patterson's Problem Two With 15% Uniform Distribution Task Variabilities

Figure 19 shows the plus or minus 15% task duration frequency distribution. It clearly shows the skewed and displaced distribution.

To examine the distribution more closely, a cumulative frequency distribution table was constructed for each of the variability levels. Table 12 summarises the results. It clearly shows, that for Patterson's problem number two with task variabilities following a uniform distribution, the Total Duration is achieved at or before the optimal Total Duration only 37% of the time.

TABLE 12

RELATIVE FREQUENCY DISTRIBUTION OF TOTAL DURATIONS FOR UNIFORMLY DISTRIBUTED TASK VARIABILITIES OF PATTERSON'S PROBLEM NUMBER TWO (1000 REPLICATIONS)

TOTAL DURATION RELATIVE TO OPTIMAL	PERCENT TOTAL DURATION ABOVE OPTIMAL FOR TASK VARIABILITY LEVELS					
	5%	15%	25%	35%	50%	75%
< Optimal	0.37	0.37	0.37	0.37	0.36	0.35
Optimal to +5%	0.63	0.37	0.22	0.14	0.09	0.07
+5% to +10%	-	0.21	0.20	0.17	0.13	0.07
+10% to +20%	-	0.05	0.19	0.23	0.21	0.16
+20% to +50%	-	-	0.02	0.09	0.21	0.30
> +50%	-	-	-	-	-	0.05

V. Conclusions and Recommendations

General Description

This chapter first draws conclusions from the results of Chapter IV, which discussed the Optimal Solution Comparison, Scheduler Performance Prediction Modelling and Optimal Solution Robustness in the Dynamic Environment. Next, the overall conclusions are presented, followed by answers to the research questions posed in Chapter I. Finally, areas of possible follow on research to this paper are discussed.

Optimal Solution Comparison

The basic problems of comparing scheduler performances were highlighted in this first simple procedure, where performance was measured by the Total Duration of the scheduled network. Specifically, the results showed that there were significant variations in performances between schedulers. But, there was no one best scheduler which produced the lowest Total Duration for all problems. Also, there were usually significant differences in schedulers' performances for the same problem. For example, in problem number seven the difference between best and worst on a single problem was 37% of the optimal Total Duration.

Overall, using the optimal solution as a benchmark and considering its average performance over Patterson's 110 problems, the best performing package was Timeline.

However, this conclusion is only partially satisfactory for a practitioner, as there may be another package with a significantly superior performance on the practitioner's particular problem or class of problems. For the practitioner, the difference in Total Duration resulting from an inappropriate use of Timeline, or any other package, can translate to unnecessary project costs or delays. For example, in the RAAF's DLM servicing of a C130E aircraft a 10% increase in Total Duration equates to an increase in aircraft down time of six days. For serious practitioners, a more definitive performance assessment of commercial software packages than an "average" performance must be made.

Scheduler Performance Prediction Models

Total Duration Prediction Models. The use of regression analysis on 58 network measures of Patterson's 110 problem set provided a good Total Duration prediction model for each of the seven software packages. Each model had low MSE, high R^2, low collinearity, good residuals and high variable commonality for one, two and three variable models. The models can be used to predict performances of individual packages for individual problems or for individual packages over a series of Patterson's problems. For a particular problem the recommended use of the models is to carry out hypothesis testing of the difference between the package Total Durations and the optimal solution Total

Durations, using a low confidence level, such as α=0.25. Poorer performing packages would be rejected by this hypothesis test as their Total Durations would be significantly different from the optimal Total Duration.

The Total Duration model with one variable is potentially an extremely useful model, as the independent variable, SADUR (sum of all task durations) is very easy to calculate for any network. The two variable model contains SADUR and ACONMX (maximum resource constrainedness using all activities as a base). ACONMX requires the calculation of the network critical path which therefore requires that the network be solved before any performance predictions can be made. Although these models appear to have great potential, Patterson's problem set has not been rigorously confirmed as representing a broad spectrum of all possible problems. It is probable that success of the Total Duration regression analysis may have actually been due to the intrinsic nature of Patterson's problem set. Therefore, further work in analysing Patterson's problem set and provision of additional regression data points for model validation would be highly desirable before the model could be used validly for more general applications.

Deviation From Optimal Total Duration Models. The models produced for Deviation From Optimal Total Duration by the regression analysis were poor. Measures other than those 58 used in this paper would need to be considered in an attempt to make the model workable. However, the encouraging results from the Total Duration models would seem to lessen the need to pursue the Deviation From Optimal Total Duration Models any further.

Optimal Solution Robustness in the Dynamic Environment

Despite the trivial nature of Patterson's problem number two, stochastic simulation of its schedule clearly showed that under conditions of task variabilities its actual Total Duration always exceeded the optimal (deterministic) Total Duration, on average.

More specifically, in this paper the conservative uniform, symmetric distribution was used to generate the variabilities. The results after 1000 replications were that, for all levels of variability, 37% of the replications had an actual duration equal or less than the optimal (deterministic) Total Duration. That is, for 63% of the replications the actual duration exceeded the optimal static Total Duration. Use of a more complex network and a less conservative distribution of task variances would very probably result in an increased overrun of actual Total Durations, due to the increased cumulative effects of statistical fluctuations in the longer critical paths.

Thus, the only time an actual Total Duration will equal the static optimal Total Duration is when there is no variability in the network. An optimal completion time can only be used confidently by a practitioner when the variability in the network is negligible. In that case, the optimal Total Duration will closely approximate the actual Duration. However, in the real world of industry, there is almost certainly some significant variability in project task durations. Therefore, the expectation that the optimal solution can actually be met is usually unrealistic. To be more useful to the practitioner, the scheduling package should therefore produce an estimated Total Duration with an assessment of the probability that the optimal Total Duration will be met. Although this concept appears similar to stochastic PERT, it is not the same, as stochastic PERT fails to address the additive nature of the Total Duration in sequentially dependent events. PERT simply sums the critical path variances to produce a wider Total Duration distribution, whereas the simulation showed that the Total Duration distribution was displaced and skewed to the right.

In the general methodology for investigation of the optimal solution robustness, use of dynamic scheduling was considered as a means of more accurately predicting the actual Total Duration of a project. Although this paper did not empirically investigate the use of dynamic scheduling, some observations may be ventured. Use of dynamic scheduling will probably improve the accuracy of a schedule as it progresses, so that the practitioner may make the optimal use of resources at each point in time. The dynamic schedule will usually be more efficient than the original static schedule. However, the dynamic rescheduling is reactive, dependent on the actual durations of tasks as they occur. In a stochastic environment, the dynamically scheduled Total Duration usually grows as the schedule progresses, and will therefore exceed the original static Total Duration. Therefore, to schedule in the dynamic world, an insightful use of time buffering would seem a superior means of scheduling.

General Conclusions

This paper has highlighted the importance of assessing quantitatively the scheduling performance of commercial project management software, and the absence of such assessments in commercial and academic literature. It further highlights the need for a series of common metrics and standard data to be used for comparative assessment of commercial software.

Total Duration proved a useful benchmark measure for comparing solutions for deterministic network problems. Likewise, Patterson's problem set is a starting point for a problem set, but this set has not been validated to ensure that it adequately represents "all" network problems, particularly large problems.

The paper also shows that scheduler performance modelling of commercial software is feasible. The inputs to such a model are measures of the network to be scheduled, and the output is an overall performance measure, such as Total Duration relative to the optimal solution. A performance measure may be obtained for single problem or for the average performance over a class of problems.

Through simulation, the validity of using deterministic optimal scheduling in real world stochastic situations was questioned. The need exists for a more realistic analysis and reporting of project network problems than is currently used. More realistic reporting would involve the prediction of a network's Total Duration with the inclusion of a probability assessment of that Total Duration being achieved.

Implications For the RAAF

There are several implications for the RAAF arising from this investigation. On average, for the test data, the measures comparing the Microplanner Professional software with the optimal solution showed Microplanner to produce Total Duration times within 8% of the optimal solution. Timeline (5.2%) and Super Project (7.1%) were superior.

However, the differences between schedulers for the specific types of networks used for DLM aircraft servicing could not been determined because of lack of information on the networks used in the RAAF's applications. Therefore, in the absence of this analysis, the RAAF should continue its use of Microplanner. As the use of project scheduling software by the RAAF for aircraft DLM task scheduling is still at the trial stage, major improvements in scheduling to produce minimum duration, robust schedules will probably be best achieved through the continued processes of refining the DLM tasks, their precedences and durations. Only when these aspects are fully refined will the added savings achievable through improved software scheduler performance become significant.

Research Questions

Question 1. The commercial packages tested using Patterson's problem set produce schedules with durations that are, on average, 5.2% to 14.1% greater than the optimal. The performance of each of the packages varied greatly across the test problems, therefore, the distribution of deviations from the optimal must also be considered. The best package produced 95% of its schedules within 15% of the optimal and the worst produced 55% of its schedules within 15%. Microplanner Professional was the third best performing scheduler, averaging 7.7% greater than the optimal and producing 83% of its schedules within 15% of the optimal.

Question 2. Regression models were constructed to predict Total Duration of networks in Patterson's problem set. The models achieved R^2 values .89 to .94 using two variables. However, when predicting software packages' performances using the models, the limitations of the models must be carefully considered to ensure that unfounded extrapolation is not performed.

Question 3. The two most significant network measures for the Total Duration model are SADUR (sum of task durations) and ACONMX (maximum resource constrainedness using all activities as a base). SADUR may be calculated by inspection of the network. To calculate ACONMX the network must first be analysed to find its critical path.

Question 4. Simulations showed that even for a trivial network, on average, task variabilities will increase the actual Total Durations of networks. The optimal solutions will only accurately predict Total Durations when the network tasks are deterministic.

Further Research

Standard metrics must be found and agreed upon by academics and industry to describe the scheduling performances of network management software packages. Standard problem sets must also be established and rigorously documented. The sets must be able to represent the universal set or a specified set of network problems. As a first step to constructing the standard set of problems, Patterson's problem set needs to be more fully analysed and documented, as some noted papers have already been based on this problem set.

The relationship of the scheduling solutions to the practical world of industry may be explored more closely. Specifically, the methodology put forward in this paper concerning the scheduling differences between static heuristic, static optimal, dynamic heuristic, dynamic optimal and the variability of industry may be examined.

An examination of the type of networks that are used in aircraft DLM task scheduling (or other specialist applications) would enable more directed investigation of schedulers which are suited to those particular applications.

Modelling the performance of scheduling packages to enable a performance prediction for a network problem is an area of further research which may prove to be particularly valuable. There are potentially great savings to industry if schedulers may be more accurately matched to network problems.

Finally, the use of "resource chains" to analyse the resource constrained network problem is a new, emerging means of approaching the scheduling solution. This field of research shows the potential to provide robust scheduling solutions in the stochastic environment.

Appendix A: Patterson's Problem Set

Origins

The set of single project multiple constrained resource network problems used in this paper is known as Patterson's problem set. It was formed by Patterson to bring together "an accumulation of all multi-resource problems in the literature today (that are readily available)" (25:860).

Patterson describes the origins of the problems in the set and their characteristics. In general terms, the problems range from 7 to 50 activities per project, with the number of immediate successor activities ranging from 1 to 5, and the number of resources ranging from 1 to 3.

Availability of Data

The Patterson Problem set was made available for this paper in electronic form by Simpson. The 110 problems were contained in one 262 KB ASCII file, named "SIMPSON.DAT". The format of this file is illustrated in Figure 20, where Patterson's problems two and three are shown.

Further Information

The large size of the problem set prevents its reproduction in this paper. However, Simpson has agreed to serve as a point of contact should readers require further information regarding his data file. His contact address is as follows:

Captain Wendell Simpson
Air Force Institute of Technology
Wright-Patterson AFB
Dayton OH 45433

```
  7[1]   3[2]   PROB002[3]
DAV1[5]                  5.[6]               5.[6]              3.[6]             7    7[4]
  1[7]        0[8]       0[9]  2[10]  3[10]  0[10]  0[10]  0[10]  0.0[11]  0.0[11]  0.0[11]

  2           0          1    4    5    0    0    0   2.0   2.0   1.0
  3           0          2    6    0    0    0    0   0.0   2.0   1.0
  4           5          2    7    0    0    0    0   3.0   3.0   3.0
  5           2          3    6    0    0    0    0   2.0   1.0   3.0
  6           5          2    7    0    0    0    0   1.0   1.0   0.0
  7           7          0    0    0    0    0    0   0.0   0.0   0.0

       13     3     PROB003
DAV2                     6.                  7.                 6.                20   20
  1           0          0    2    3    0    0    0   0.0   0.0   0.0
  2           0          3    4    5    0    0    0   3.0   2.0   1.0
  3           0          5    8    0    0    0    0   2.0   4.0   2.0
  4           5          6   10    0    0    0    0   3.0   1.0   2.0
  5           3          2    6    7    0    0    0   4.0   3.0   1.0
  6           9          3   11    0    0    0    0   2.0   0.0   3.0
  7          12          3   13    0    0    0    0   1.0   1.0   1.0
  8           5          4    9    0    0    0    0   3.0   1.0   1.0
  9          12          5   13    0    0    0    0   2.0   2.0   2.0
 10          11          4   11    0    0    0    0   3.0   2.0   3.0
 11          15          2   12    0    0    0    0   4.0   1.0   0.0
 12          17          3   13    0    0    0    0   5.0   4.0   2.0
 13          20          0    0    0    0    0    0   0.0   0.0   0.0
```

Notes:
1. Total number of activities in problem
2. Total number of resources used (1 to 5)
3. Problem name (1 to 110)
4. Talbot's Optimal schedule length
5. Patterson's problem identification
6. Total resources available (for 1 to 5 resources)
7. Activity numbers
8. Optimal Solution activity start time
9. Activity Durations
10. Activity number(s) of follower activities
11. Resource consumption for activity (per period)

Figure 20. Format of Simpson's ASCII File

Appendix B: Scheduling Patterson's Problem Set With Microplanner Professional

Patterson Problem Set Data Conversion

The format of Patterson's problem set, as provided by Simpson, is detailed in Appendix A. However, the format required by Microplanner Professional for ASCII data input, shown in Figure 21, is significantly different to that of Simpson's file. To avoid the massive effort of manual transcription of all Patterson problems from Simpson's format to the Microplanner Professional format, a FORTRAN conversion programme was written and used successfully. The listing is shown in Figure 22.

Scheduling Using Microplanner Professional

Most of the data for each problem set could be imported using the ASCII text import feature. However, it was necessary to input manually the quantities of resources available, the number of days in the working week, the type of network used (activity-on-arrow or activity-on-node), type of calendars to use (using calendar days or numeric days), and several other calculation parameters for each of the 110 problems. The process was repetitive and time consuming because only very limited software macros are available in Microplanner.

The project scheduler settings used are shown in Table 13.

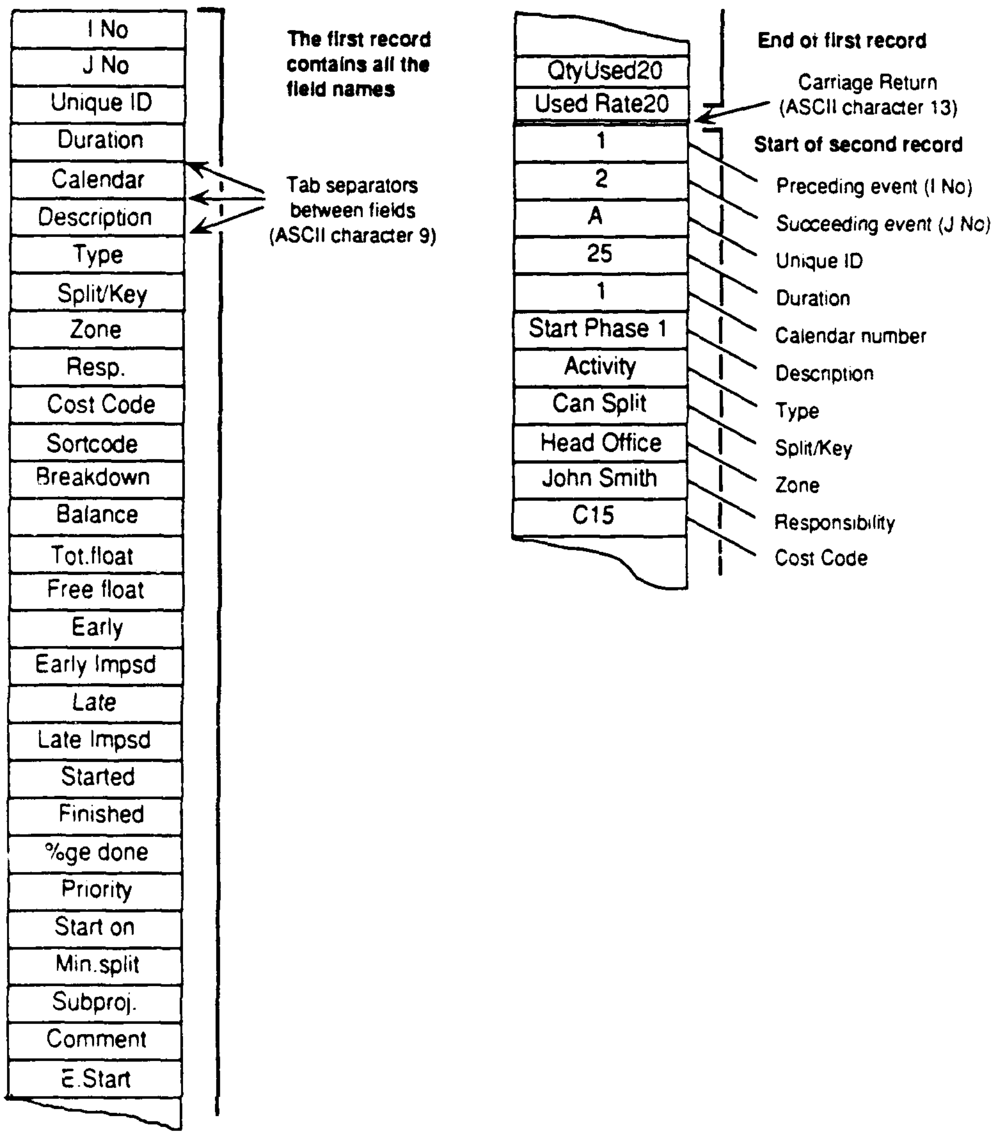

Figure 21. Text Import File Format (21:771)

```
C*****************************************************************
C*****************************************************************
C*                                                               *
C*          CONVERSION FROM PATTERSON'S PROBLEM SET FORMAT       *
C*          TO MICROPLANNER PROFESSIONAL TEXT IMPORT FORMAT      *
C*                                                               *
C*           Written by Kerry M. Bayley          June 1991       *
C*                                                               *
C*                         for  VAX FORTRAN 5.6                  *
C*                              MICROPLANNER PROFESSIONAL 7.3b   *
C*                                                               *
C*          * This programme is file 'CONVERTA.FOR'              *
C*                                                               *
C*****************************************************************
C*****************************************************************
C*              DECLARATION AND INITIALISATION                   *
C*****************************************************************
      INTEGER  NACTIVITIES,NRESOURCES,IDURATION(55),IFOLLOW(55,5)
      REAL     RESOURCE(55,3)
      CHARACTER*7 PROBNAME
      CHARACTER*1 TAB
      TAB=CHAR(9)
      OPEN (UNIT=1,FILE='SIMPSON.DAT',STATUS='OLD')
C*****************************************************************
C*              READ IN DATA                                     *
C*****************************************************************
   10 CONTINUE
C
C   Read in problem title data
C
      READ (1,20) NACTIVITIES,NRESOURCES,PROBNAME
   20 FORMAT (/3X,I2,4X,I1,4X,A7/)
      IF (NACTIVITIES.EQ.0) GO TO 200          ! Test for end
      OPEN (UNIT=2,FILE=PROBNAME,STATUS='NEW')  ! Open outputfile
C
C   Read in current problem main data
C    (activity, followers, duration, resource usage)
C
      DO 40 I=1,NACTIVITIES
          READ (1,30) IDURATION(I),(IFOLLOW(I,J),J=1,5),
     +    (RESOURCE(I,J),J=1,3)
   30     FORMAT (26X,6I4,3F5.1)
   40 CONTINUE
C*****************************************************************
C*              CONVERSION AND OUTPUT                            *
C*****************************************************************
C
C    Write the header record
C
      WRITE (2,50) (TAB,K=1,17)
   50 FORMAT ('+ ','INo',A1,'JNo',A1,'Duration',A1,'Calendar',A1,
     +'Type',A1,'Split/Key',A1,
     +'Name1',A1,'Res%1',A1,'Qty1',A1,'Usage1',A1,
     +'Name2',A1,'Res%2',A1,'Qty2',A1,'Usage2',A1,
     +'Name3',A1,'Res%3',A1,'Qty3',A1,'Usage3')
C
C   Write current problem data records
C
      DO 100 I=1,NACTIVITIES            ! Start current problem loop
          INDEX=1
          IF ((IDURATION(I).EQ.0).OR.((RESOURCE(I,1)
```

```
     +     +RESOURCE(I,2)+RESOURCE(I,3)).EQ.0)) THEN
               WRITE (2,55) I,TAB,TAB,IDURATION(I),TAB,TAB,TAB
 55            FORMAT (' ',I2,2A1,I4,A1,'1',A1,'Task',
     +         A1,'Non-Split')
           ELSE
               WRITE (2,60) I,TAB,TAB,IDURATION(I),
     +         TAB,TAB,TAB,TAB,
     +         TAB,TAB,RESOURCE(I,1),TAB,TAB,
     +         TAB,TAB,RESOURCE(I,2),TAB,TAB,
     +         TAB,TAB,RESOURCE(I,3),TAB,TAB
 60            FORMAT (' ',I2,2A1,I4,A1,'1',A1,'Task',
     +         A1,'Non-Split',A1,
     +         'RE1',A1,'100',A1,F5.1,A1,'PerUnit',A1,
     +         'RE2',A1,'100',A1,F5.1,A1,'PerUnit',A1,
     +         'RE3',A1,'100',A1,F5.1,A1,'PerUnit',A1)
           ENDIF
 80        CONTINUE                           ! Start followers loop
           DO WHILE ((IFOLLOW(I,INDEX).NE.0).AND.(INDEX.LE.5))
               WRITE (2,90) I,TAB,IFOLLOW(I,INDEX),
     +         TAB,TAB,TAB
 90            FORMAT (' ',I2,A1,I4,A1,'0',A1,'1',A1,'Fin->St')
               INDEX=INDEX+1
           END DO                             ! End followers loop
100    CONTINUE                       ! End current problem loop
C
C  Reset for the next problem data set
C
       CLOSE (UNIT=2)                        ! Close output file
       GO TO 10                              ! Next problem
C*****************************************************************
C              PROGRAMME TERMINATION                             *
C*****************************************************************
200    CLOSE (UNIT=1)                        ! Close input data file
       STOP
       END
```

Figure 22. FORTRAN Conversion Programme

TABLE 13

MANUALLY INPUT SETTINGS FOR THE MICROPLANNER PROFESSIONAL SCHEDULER

PARAMETER	SETTING
Technique	Precedence (Activity-On-Node)
Time Units	Day, None, None
Date Type	Numeric
Split Tasks for Resource Analysis	No
Time Now Date	1
Float to Longest Path	Yes
Working Week	7 Days
Time Analysis	Yes
Resource Analysis Type	Resource Critical
Resource Usage Value	Quantity equals Threshold

Problems Encountered

Scheduling with Microplanner Professional proved more time consuming than expected. The first version of the software received from Microplanner International, Ver 7.3a, would not export/import data correctly. A copy of Ver 7.3b, which was subsequently supplied by Microplanner International, did not have the same deficiencies. However, the lack of detail in the technical documentation concerning data importation resulted in much trial and error when coding the FORTRAN conversion programme and importing the problem sets. Details of methodology and validity checking are contained in the Methodology section (Chapter III) and Results section (Chapter IV).

Appendix C: Project Network Summary Measures

Background

The 58 project measures used in this paper are relevant measures extracted from Simpson's doctoral dissertation (33:203-217). In that paper, Simpson constructed and collected from the literature 130 measures that describe the characteristics of project networks. The measures range in complexity from the number of tasks in the network to complicated resource analysis measures.

Notation For Project Network Measures

The following notation is used to describe the measures:

NJ	Number of activities/jobs/nodes in the project network (using activity-on-node representation)
j	Task number, j=1,...,NJ
d_j	Duration of task j
P_j	Number of immediate predecessor of task j
S_t	Number of immediate successors of task j
TS_j	Total slack for activity j
FS_j	Free slack for activity j
K	Number of resource types
k	Resource index, k=1,...,K
r_{jk}	Amount of resource k needed by task j each time task j is active
t	Time period index
R_{kt}	Amount of resource k available in time period t

CP The duration of the critical path

x_{jt} A 0-1 variable to indicate whether task j is active in period t. The all early start schedule determines the values.

$$x_{jt} = \left\{ \begin{matrix} 1 & \textit{if activity } j \textit{ is active in period } t \\ 0 & \textit{otherwise} \end{matrix} \right\} \quad \textbf{(2)}$$

Project Summary Measures

NJ Number of tasks/activities

CP Length of critial path

NARC Number of arcs in the project network

SADUR Sum of task durations

$$\sum_{j=1}^{NJ} d_j \quad \textbf{(3)}$$

AADUR Average task duration

$$\frac{SADUR}{NJ} \quad \textbf{(4)}$$

VADUR Variance in task duration

$$\frac{\sum_{j=1}^{NJ} (d_j - AADUR)^2}{NJ-1} \quad \textbf{(5)}$$

COMPLX Complexity

$$\frac{NARC}{NJ} \quad \textbf{(6)}$$

STLSLK Sum of task total slack

$$\sum_{j=1}^{NJ} TS_j \tag{7}$$

NTLSLK Number of task with total slack

$$\sum_{j=1}^{NJ} \{ {1 \ if \ TS_j > 0 \atop 0 \ if \ TS_j = 0} \} \tag{8}$$

PTLSLK Percent of tasks with total slack

$$\frac{NTLSLK}{NJ} \tag{9}$$

ATLSLK Average total slack per task

$$\frac{STLSLK}{NJ} \tag{10}$$

TSLRAT Total slack ratio

$$\frac{STLSLK}{CP} \tag{11}$$

ASLRAT Average slack ratio

$$\frac{ATLSLK}{CP} \tag{12}$$

PDENT Project density (total slack)

$$\frac{SADUR}{SADUR + STLSLK} \tag{13}$$

SFRSLK Sum of task free slack

$$\sum_{j=1}^{NJ} FS_j \tag{14}$$

NFRSLK Number of tasks with free slack

$$\sum_{j=1}^{NJ} \begin{Bmatrix} 1 \ if \ FS_j > 0 \\ 0 \ if \ FS_j = 0 \end{Bmatrix} \tag{15}$$

PFRSLK Percent of tasks with free slack

$$\frac{NFRSLK}{NJ} \tag{16}$$

AFRSLK Average free slack per task

$$\frac{SFRSLK}{NJ} \tag{17}$$

PDENF Project density (free slack)

$$\frac{SADUR}{SADUR + SFRSLK} \tag{18}$$

PCTMIN Minimum percent of tasks demanding a resource

$$\min \{PCT_k\} \tag{19}$$

where PCT is the percent of activities requiring positive amount of resource k:

$$PCT = \frac{\sum_{j=1}^{NJ} \begin{Bmatrix} 1 \ if \ r_{jk} > 0 \\ 0 \ if \ r_{jk} = 0 \end{Bmatrix}}{NJ} . \tag{20}$$

PCTAVG Average percent of tasks demanding a resource

$$\frac{\sum_{k=1}^{K} PCT_k}{K} \tag{21}$$

PCTMAX Maximum percent of tasks demanding a resource

$$\max \{PCT_k\} \tag{22}$$

UTLMIN Minimum resource utilisation

$$\min\{UTIL_k\} \tag{23}$$

where UTIL is the utilisation of resource k over the critical path length:

$$UTIL = \frac{\sum_{j=1}^{NJ} r_{jk} \cdot d_j}{\sum_{t=1}^{CP} R_{kt}} \tag{24}$$

AUTIL Average resource utilisation

$$\frac{\sum_{k=1}^{K} UTIL_k}{K} \tag{25}$$

UTLMAX Maximum resource utilisation

$$\max\{UTIL_k\} \tag{26}$$

ADMND Average quantity of resources demanded when demanded

$$\frac{\sum_{k=1}^{K} DMND_k}{K} \tag{27}$$

where DMND is the average amount of resource k demanded when required by an activity:

$$DMND_k = \frac{\sum_{j=1}^{NJ} r_{jk}}{\sum_{j=1}^{NJ} \left\{ \begin{array}{l} 1 \text{ if } r_{jk} > 0 \\ 0 \text{ if } r_{jk} = 0 \end{array} \right\}} \tag{28}$$

CONMIN Minimum resource constrainedness

$$\min\{CONST_k\} \tag{29}$$

where CONST is the resource constrainedness using the average availabilities over CP horizon as a base:

$$CONST_k = \frac{DMND}{\sum_{t=1}^{CP} \frac{R_{kt}}{CP}} \tag{30}$$

CONAVG Average resource constrainedness

$$\frac{\sum_{k=1}^{K} CONST_k}{K} \tag{31}$$

CONMAX Maximum resource constrainedness

$$\max \{CONST_k\} \tag{32}$$

CONVAR Variance in resource constrainedness

$$\frac{\sum_{k=1}^{K} (CONST_k - CONAVG)^2}{K - 1} \tag{33}$$

TCONMN Minimum resource constrainedness over time

$$\min \{TCONST_k\} \tag{34}$$

where TCONST is the resource constrainedness over time on the critical path:

$$TCONST_k = \frac{\sum_{j=1}^{NJ} r_{jk} \cdot d_j}{\{\sum_{j=1}^{NJ} \{\begin{matrix} 1 & if\ r_{jk} > 0 \\ 0 & if\ r_{jk} = 0 \end{matrix} \}\} \cdot \{\sum_{t=1}^{CP} R_{kt} \}} \tag{35}$$

TCONAV Average resource constrainedness over time

$$\frac{\sum_{k=1}^{K} TCONST_k}{K} \tag{36}$$

TCONMX Maximum resource constrainedness over time

$$\max \{TCONST_k\} \tag{37}$$

TCONVR Variance in resource constrainedness over time

$$\frac{\sum_{k=1}^{K} (TCONST_k - TCONAV)^2}{K - 1} \tag{38}$$

ACONMN Minimum constrainedness using all activities as a base

$$\min \{ACONST_k\} \tag{39}$$

where ACONST is the resource constrainedness using all activities as a base:

$$ACONST_k = \frac{\sum_{j=1}^{NJ} r_{jk}}{NJ \cdot \{\sum_{t=1}^{CP} \frac{R_{kt}}{CP}\}} \tag{40}$$

ACONAV Average constrainedness using all activities as a base

$$\frac{\sum_{k=1}^{K} ACONST_k}{K} \tag{41}$$

ACONMX Maximum constrainedness using all activities as a base

$$\max \{ACONST_k\} \tag{42}$$

ACONVR Variance in resource constrainedness using all activities as a base

$$\frac{\sum_{k=1}^{K} (ACONST_k - ACONAV)^2}{K - 1} \tag{43}$$

TDEN Total density

$$\sum_{j=1}^{NJ} \max\{0, P_j - S_j\} \tag{44}$$

ADEN Average density

$$\frac{TDEN}{NJ} \tag{45}$$

$OFACT_k$ Obstruction factor based on an early start schedule

$$\frac{\sum_{t=1}^{CP} \max\{0, \{\sum_{j=1}^{NJ} x_{jt} \cdot r_{jk}\} - R_{kt}\}}{\sum_{k=1}^{NJ} r_{jk} \cdot d_j} \tag{46}$$

OFACTT Total obstruction factor

$$\sum_{k=1}^{K} OFACT_k \tag{47}$$

OFACTN Minimum obstruction factor

$$\min\{OFACT_k\} \tag{48}$$

OFACTX Maximum obstruction factor

$$\max\{OFACT_k\} \tag{49}$$

$FFACT_k$ Underutilisation factor based on an all early start schedule

$$\frac{\sum_{t=1}^{CP} \max\{0, R_{kt} - \{\sum_{j=1}^{NJ} x_{jt} \cdot r_{jk}\}\}}{\sum_{k=1}^{NJ} r_{jk} \cdot d_j} \tag{50}$$

FFACTT Total underutilisation factor

$$\sum_{k=1}^{K} FFACT_k \tag{51}$$

FFACTN Minimum underutilisation factor

$$\min\{FFACT_k\} \tag{52}$$

FFACTX Maximum underutilisation factor

$$\max\{FFACT_k\} \tag{53}$$

MINNOO Minimum number of periods over

$$\min\{NOO_k\} \tag{54}$$

where NOO_k is the number of periods that demand exceeds availability for resource k based on an all early start schedule:

$$NOO_k = \sum_{t=1}^{CP} \left\{ \begin{array}{ll} 1 & if \ \sum_{j=1}^{NJ} x_{jt} \cdot r_{jk} > R_{kt} \\ 0 & if \ \sum_{j=1}^{NJ} x_{jt} \cdot r_{jk} \le R_{kt} \end{array} \right\} \tag{55}$$

ANOOV Average number of periods over

$$\frac{\sum_{k=1}^{K} NOO_k}{K} \tag{56}$$

MAXNOO Maximum number of periods over

$$\max\{NOO_k\} \tag{57}$$

MINNOU Minimum number of periods under

$$\min\{NOU_k\} \tag{58}$$

where NOU_k is the number of periods that demand exceeds availability for resource k based on an all early start schedule:

$$NOU_k = \sum_{t=1}^{CP} \left\{ \begin{array}{ll} 1 & if \sum_{j=1}^{NJ} x_{jt} \cdot r_{jk} \le R_{kt} \\ 0 & if \sum_{j=1}^{NJ} x_{jt} \cdot r_{jk} > R_{kt} \end{array} \right\} \tag{59}$$

ANOUN Average number of periods under

$$\frac{\sum_{k=1}^{K} NOU_k}{K} \tag{60}$$

MAXNOU Maximum number of periods under

$$\max \{NOU_k\} \tag{61}$$

SUMCON Number of periods in which demand exceeds availability for at least one resource based on an all early start schedule

$$\sum_{t=1}^{CP} \left\{ \begin{array}{ll} 1 & if \ \max\{\sum_{j=1}^{NJ} x_{jt} \cdot r_{jk} - R_{kt}\} > 0 \\ 0 & if \ \max\{\sum_{j=1}^{NJ} x_{jt} \cdot r_{jk} - R_{kt}\} \le 0 \end{array} \right\} \tag{62}$$

PERCON Percent of periods in which demand exceeds availability for at least one resource based on an all early start schedule

$$\frac{SUMCON}{CP} \tag{63}$$

ARLFSM Sum of average resource load factors

$$\sum_{k=1}^{K} ARLF_k \tag{64}$$

where $ARLF_k$ is the average resource load factor for resource k based on an all early start schedule:

$$ARLF_k = \frac{1}{CP} \cdot \sum_{t=1}^{CP} \sum_{j=1}^{NJ} z_t \cdot x_{jt} \cdot \{ \frac{r_{jk}}{\sum_{k=1}^{K} \{ {1 \text{ if } r_{jk} > 0 \atop 0 \text{ if } r_{jk} = 0} \}} \} \quad \textbf{(65)}$$

and where:

$$z_t = \{ \begin{matrix} 1 & if\ t > \frac{CP}{2} \\ -1 & if\ t \leq \frac{CP}{2} \end{matrix} \} \quad \textbf{(66)}$$

ARLSM Minimum average resource load factors

$$\sum_{k=1}^{K} ARLFSM_k \quad \textbf{(67)}$$

ARLFMN Minimum average resource load factor

$$\min \{ARLF_k\} \quad \textbf{(68)}$$

ARLFAV Average of average resource load factor

$$\frac{ARLFSM}{K} \quad \textbf{(69)}$$

ARLFMX Maximum average resource load factor

$$\max \{ARLF_k\} \quad \textbf{(70)}$$

Appendix D: SAS Regression Programme

Total Duration Times Against Patterson's Problem Set Measures

```
*************************************************************************;
*                                                                      *;
*       REGRESSION MODELLING OF TOTAL DURATION AS A FUNCTION           *;
*       OF 58 "NETWORK MEASURES" FOR SIX COMMERCIAL SOFTWARE           *;
*          PACKAGES USING PATTERSON'S 110 PROBLEM SET                  *;
*                                                                      *;
*          Written by Kerry M. Bayley                 June 1991        *;
*                    for VAX SAS 6.06                                  *;
*                                                                      *;
*************************************************************************;
*    DECLARATION & READ IN DATA FILES                                  *;
*************************************************************************;
FILENAME TIMES 'TIMES.DAT';
FILENAME MEASURES 'MEASURES.DAT';
OPTIONS PAGESIZE=66 LINESIZE=80;
DATA PROJMEAS;
    INFILE MEASURES RECFM=F LRECL=80;
    INPUT TITLE $ 1-5 IRULE1 ITIE1 IREV1
    #2 CP 1-4 NNODE 6-8 NDUMMY 9-11 NARC 12-14 NFRSLK 15-17 NTLSLK
       18-20 STLSLK 21-24 SFRSLK 26-29 SADUR 31-34 AADUR 36-42 VADUR
       43-49 COMPLX 50-55 ADMND 56-62
    #3 AFRSLK 1-5 ATLSLK 6-10 PFRSLK 11-16 PTLSLK 17-22 ASLRAT  23-28
       TSLRAT 29-34 UTLMIN 35-40 AUTIL 41-46 UTLMAX 47-52 PCTMIN 53-58
       PCTMAX 59-64 PCTAVG 65-70
    #4 CONMAX 1-7 CONAVG 8-14 CONMIN 15-21 CONVAR 22-28 TCONMX 29-35
       TCONAV 36-42 TCONMN 43-49 TCONVR 50-56
    #5 ACONAV 1-7 ACONMX 8-14 ACONMN 15-21 ACONVR 22-28 PDENT 29-35
       DENF 36-42
    #6 MAXNOO 1-4 MINNOO 5-8 MAXNOU 9-12 MINNOU 13-16 ANOOV 17-22 ANOUN
       23-28 OFACTT 29-35 OFACTX 36-42 OFACTN 43-49 FFACTT 50-56 FFACTX
       57-63 FFACTN 64-70
    #7 ARLFMN 1-9 ARLFMX 10-18 ARLFSM 19-27 ARLFAV 28-36 SUMCON 37-45
       PERCON 46-54 TDEN 55-63 ADEN 64-72
    #8
    #9
    #10
    #11
    #12
    #13
    #14;
DATA SOLTIMES;
    INFILE TIMES LRECL=80;
    INPUT TITLE $ TALBOT TSUPER TTIME THARV TPRIM1 TPRIM2 TMICRO;
*************************************************************************;
*    SORT & MERGE DATA FILES                                           *;
*************************************************************************;
PROC SORT DATA=PROJMEAS;
```

```
    BY TITLE;
PROC SORT DATA=SOLTIMES;
    BY TITLE;
DATA COMBINED;
    MERGE PROJMEAS SOLTIMES;
      BY TITLE;
**********************************************************************;
*    STEPWISE REGRESSION PROCEDURES                                  *;
*     (Using the MAXR option to find the highest R^2 value model     *;
*       for a stated number of independent variables in the model)   *;
**********************************************************************;
PROC STEPWISE DATA=COMBINED;
   TITLE 'SAS STEPWISE REGRESSION FOR DURATION TIMES.';
   MODEL TALBOT =      NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK
                       SADUR AADUR VADUR COMPLX ADMND AFRSLK ATLSLK
                       PFRSLK PTLSLK ASLRAT TSLRAT UTLMIN AUTIL UTLMAX
                       PCTMIN PCTMAX PCTAVG CONMAX CONAVG CONMIN CONVAR
                       TCONMX TCONAV TCONMN TCONVR ACONAV
                       ACONMX ACONMN ACONVR PDENT PDENF MAXNOO MINNOO
                       MAXNOU MINNOU ANOOV ANOUN OFACTT OFACTX OFACTN
                       FFACTT FFACTX FFACTN ARLFMN ARLFMX ARLFSM ARLFAV
                       SUMCON PERCON TDEN ADEN / MAXR STOP=15;
   MODEL TSUPER =      NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK
                       SADUR AADUR VADUR COMPLX ADMND AFRSLK ATLSLKPFRSLK
                       PTLSLK ASLRAT TSLRAT UTLMIN AUTIL UTLMAX PCTMIN
                       PCTMAX PCTAVG CONMAX CONAVG CONMIN CONVAR TCONMX
                       TCONAV TCONMN TCONVR ACONAV ACONMX ACONMN ACONVR
                       PDENT PDENF MAXNOO MINNOO MAXNOU MINNOU ANOOV
                       ANOUN OFACTT OFACTX OFACTN FFACTT FFACTX FFACTN
                       ARLFMN ARLFMX ARLFSM ARLFAV SUMCON PERCON TDEN
                       ADEN / MAXR STOP=15;
   MODEL TTIME =       NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK
                       SADUR AADUR VADUR COMPLX ADMND AFRSLK ATLSLK
                       PFRSLK PTLSLK ASLRAT TSLRAT UTLMIN AUTIL UTLMAX
                       PCTMIN PCTMAX PCTAVG CONMAX CONAVG CONMIN CONVAR
                       TCONMX TCONAV TCONMN TCONVR ACONAV ACONMX ACONMN
                       ACONVR PDENT PDENF MAXNOO MINNOO MAXNOU MINNOU
                       ANOOV ANOUN OFACTT OFACTX OFACTN FFACTT FFACTX
                       FFACTN ARLFMN ARLFMX ARLFSM ARLFAV SUMCON PERCON
                       TDEN ADEN / MAXR STOP=15;
   MODEL THARV =       NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK
                       SADUR AADUR VADUR COMPLX ADMND AFRSLK ATLSLK
                       PFRSLK PTLSLK ASLRAT TSLRAT UTLMIN AUTIL UTLMAX
                       PCTMIN PCTMAX PCTAVG CONMAX CONAVG CONMIN CONVAR
                       TCONMX TCONAV TCONMN TCONVR ACONAV ACONMX ACONMN
                       ACONVR PDENT PDENF MAXNOO MINNOO MAXNOU MINNOU
                       ANOOV ANOUN OFACTT OFACTX OFACTN FFACTT FFACTX
                       FFACTN ARLFMN ARLFMX ARLFSM ARLFAV SUMCON PERCON
                       TDEN ADEN / MAXR STOP=15;
   MODEL TPRIM1 =      NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK
                       SADUR AADUR VADUR COMPLX ADMND AFRSLK ATLSLK
                       PFRSLK PTLSLK ASLRAT TSLRAT UTLMIN AUTIL UTLMAX
                       PCTMIN PCTMAX PCTAVG CONMAX CONAVG CONMIN CONVAR
```

```
                    TCONMX TCONAV TCONMN TCONVR ACONAV ACONMX ACONMN
                    ACONVR PDENT PDENF MAXNOO MINNOO MAXNOU MINNOU
                    ANOOV ANOUN OFACTT OFACTX OFACTN FFACTT FFACTX
                    FFACTN ARLFMN ARLFMX ARLFSM ARLFAV SUMCON PERCON
                    TDEN ADEN / MAXR STOP=15;
   MODEL TPRIM2 =   NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK
                    SADUR AADUR VADUR COMPLX ADMND AFRSLK ATLSLK
                    PFRSLK PTLSLK ASLRAT TSLRAT UTLMIN AUTIL UTLMAX
                    PCTMIN PCTMAX PCTAVG CONMAX CONAVG CONMIN CONVAR
                    TCONMX TCONAV TCONMN TCONVR ACONAV ACONMX ACONMN
                    ACONVR PDENT PDENF MAXNOO MINNOO MAXNOU MINNOU
                    ANOOV ANOUN OFACTT OFACTX OFACTN FFACTT FFACTX
                    FFACTN ARLFMN ARLFMX ARLFSM ARLFAV SUMCON PERCON
                    TDEN ADEN / MAXR STOP=15;
   MODEL TMICRO =   NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK
                    SADUR AADUR VADUR COMPLX ADMND AFRSLK ATLSLK
                    PFRSLK PTLSLK ASLRAT TSLRAT UTLMIN AUTIL UTLMAX
                    PCTMIN PCTMAX PCTAVG CONMAX CONAVG CONMIN CONVAR
                    TCONMX TCONAV TCONMN TCONVR ACONAV ACONMX ACONMN
                    ACONVR PDENT PDENF MAXNOO MINNOO MAXNOU MINNOU
                    ANOOV ANOUN OFACTT OFACTX OFACTN FFACTT FFACTX
                    FFACTN ARLFMN ARLFMX ARLFSM ARLFAV SUMCON PERCON
                    TDEN ADEN / MAXR STOP=15;
ENDSAS;
*************************************************************************;
*     END OF PROGRAMME                                                  *;
*************************************************************************;
```

Appendix E: SAS Regression Programme

Deviation From Optimal Total Duration Times Against Patterson's Problem Set Measures

```
*********************************************************************;
*                                                                   *;
*    REGRESSION MODELLING OF "DEVIATION OF TOTAL DURATION FROM      *;
*     OPTIMAL" AS A FUNCTION OF 58 "NETWORK MEASURES" FOR SIX       *;
*   COMMERCIAL SOFTWARE PACKAGES USING PATTERSON'S 110 PROBLEM SET  *;
*                                                                   *;
*         Written by Kerry M. Bayley                June 1991       *;
*                   for VAX SAS 6.06                                *;
*                                                                   *;
*********************************************************************;
*   DECLARATION & READ IN DATA FILES                                *;
*********************************************************************;
FILENAME TIMES 'TIMESDIF.DAT';
FILENAME MEASURES 'MEASURES.DAT';
OPTIONS PAGESIZE=66 LINESIZE=80;
DATA PROJMEAS;
   INFILE MEASURES RECFM=F LRECL=80;
   INPUT TITLE $ 1-5 IRULE1 ITIE1 IREV1
     #2  CP 1-4 NNODE 6-8 NDUMMY 9-11 NARC 12-14 NFRSLK 15-17 NTLSLK
         18-20 STLSLK 21-24 SFRSLK 26-29 SADUR 31-34 AADUR 36-42
         VADUR 43-49 COMPLX 50-55 ADMND 56-62
     #3  AFRSLK 1-5 ATLSLK 6-10 PFRSLK 11-16 PTLSLK 17-22 ASLRAT 23-28
         TSLRAT 29-34 UTLMIN 35-40 AUTIL 41-46 UTLMAX 47-52 PCTMIN 53-58
         PCTMAX 59-64 PCTAVG 65-70
     #4  CONMAX 1-7 CONAVG 8-14 CONMIN 15-21 CONVAR 22-28 TCONMX 29-35
         TCONAV 36-42 TCONMN 43-49 TCONVR 50-56
     #5  ACONAV 1-7 ACONMX 8-14 ACONMN 15-21 ACONVR 22-28 PDENT 29-35
         PDENF 36-42
     #6  MAXNOO 1-4 MINNOO 5-8 MAXNOU 9-12 MINNOU 13-16.ANOOV 17-22
         ANOUN 23-28 OFACTT 29-35 OFACTX 36-42 OFACTN 43-49 FFACTT 50-56
         FFACTX 57-63 FFACTN 64-70
     #7  ARLFMN 1-9 ARLFMX 10-18 ARLFSM 19-27 ARLFAV 28-36 SUMCON 37-45
         PERCON 46-54 TDEN 55-63 ADEN 64-72
     #8
     #9
     #10
     #11
     #12
     #13
     #14;
DATA SOLTIMES;
   INFILE TIMES LRECL=80;
   INPUT TITLE $ TSUPER TTIME THARV TPRIM1 TPRIM2 TMICRO;
*********************************************************************;
*   SORT & MERGE DATA FILES                                         *;
*********************************************************************;
PROC SORT DATA=PROJMEAS;
```

```
    BY TITLE;
PROC SORT DATA=SOLTIMES;
    BY TITLE;
DATA COMBINED;
   MERGE PROJMEAS SOLTIMES;
    BY TITLE;
**********************************************************************;
*    STEPWISE REGRESSION PROCEDURES                                  *;
*     (Using the MAXR option to find the highest R^2 value model     *;
*       for a stated number of independent variables in the model)   *;
**********************************************************************;
PROC STEPWISE DATA=COMBINED;
   TITLE 'SAS STEPWISE REGRESSION FOR DEVIATION FROM OPTIMAL TIMES.';
   MODEL TSUPER = NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK SADUR
                  AADUR VADUR COMPLX ADMND AFRSLK ATLSLK PFRSLK PTLSLK
                  ASLRAT TSLRAT UTLMIN AUTIL UTLMAX PCTMIN PCTMAX
                  PCTAVG CONMAX CONAVG CONMIN CONVAR TCONMX TCONAV
                  TCONMN TCONVR ACONAV ACONMX ACONMN ACONVR PDENT
                  PDENF MAXNOO MINNOO MAXNOU MINNOU ANOOV ANOUN
                  OFACTT OFACTX OFACTN FFACTT FFACTX FFACTN ARLFMN
                  ARLFMX ARLFSM ARLFAV SUMCON PERCON TDEN ADEN
                  / MAXR STOP=15;
   MODEL TTIME = NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK SADUR
                  AADUR VADUR COMPLX ADMND AFRSLK ATLSLK PFRSLK PTLSLK
                  ASLRAT TSLRAT UTLMIN AUTIL UTLMAX PCTMIN PCTMAX
                  PCTAVG CONMAX CONAVG CONMIN CONVAR TCONMX TCONAV
                  TCONMN TCONVR ACONAV ACONMX ACONMN ACONVR PDENT
                  PDENF MAXNOO MINNOO MAXNOU MINNOU ANOOV ANOUN
                  OFACTT OFACTX OFACTN FFACTT FFACTX FFACTN ARLFMN
                  ARLFMX ARLFSM ARLFAV SUMCON PERCON TDEN ADEN
                  / MAXR STOP=15;
   MODEL THARV = NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK SADUR
                  AADUR VADUR COMPLX ADMND AFRSLK ATLSLK PFRSLK PTLSLK
                  ASLRAT TSLRAT UTLMIN AUTIL UTLMAX PCTMIN PCTMAX
                  PCTAVG CONMAX CONAVG CONMIN CONVAR TCONMX TCONAV
                  TCONMN TCONVR ACONAV ACONMX ACONMN ACONVR PDENT
                  PDENF MAXNOO MINNOO MAXNOU MINNOU ANOOV ANOUN
                  OFACTT OFACTX OFACTN FFACTT FFACTX FFACTN ARLFMN
                  ARLFMX ARLFSM ARLFAV SUMCON PERCON TDEN ADEN
                  / MAXR STOP=15;
   MODEL TPRIM1 = NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK SADUR
                  AADUR VADUR COMPLX ADMND AFRSLK ATLSLK PFRSLK PTLSLK
                  ASLRAT TSLRAT UTLMIN AUTIL UTLMAX PCTMIN PCTMAX
                  PCTAVG CONMAX CONAVG CONMIN CONVAR TCONMX TCONAV
                  TCONMN TCONVR ACONAV ACONMX ACONMN ACONVR PDENT
                  PDENF MAXNOO MINNOO MAXNOU MINNOU ANOOV ANOUN
                  OFACTT OFACTX OFACTN FFACTT FFACTX FFACTN ARLFMN
                  ARLFMX ARLFSM ARLFAV SUMCON PERCON TDEN ADEN
                  / MAXR STOP=15;
   MODEL TPRIM2 = NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK SADUR
                  AADUR VADUR COMPLX ADMND AFRSLK ATLSLK PFRSLK PTLSLK
                  ASLRAT TSLRAT UTLMIN AUTIL UTLMAX PCTMIN PCTMAX
                  PCTAVG CONMAX CONAVG CONMIN CONVAR TCONMX TCONAV
```

```
                    TCONMN TCONVR ACONAV ACONMX ACONMN ACONVR PDENT
                    PDENF MAXNOO MINNOO MAXNOU MINNOU ANOOV ANOUN
                    OFACTT OFACTX OFACTN FFACTT FFACTX FFACTN ARLFMN
                    ARLFMX ARLFSM ARLFAV SUMCON PERCON TDEN ADEN
                    / MAXR STOP=15;
   MODEL TMICRO = NNODE NDUMMY NARC NFRSLK NTLSLK STLSLK SFRSLK SADUR
                    AADUR VADUR COMPLX ADMND AFRSLK ATLSLK PFRSLK PTLSLK
                    ASLRAT TSLRAT UTLMIN AUTIL UTLMAX PCTMIN PCTMAX
                    PCTAVG CONMAX CONAVG CONMIN CONVAR TCONMX TCONAV
                    TCONMN TCONVR ACONAV ACONMX ACONMN ACONVR PDENT
                    PDENF MAXNOO MINNOO MAXNOU MINNOU ANOOV ANOUN
                    OFACTT OFACTX OFACTN FFACTT FFACTX FFACTN ARLFMN
                    ARLFMX ARLFSM ARLFAV SUMCON PERCON TDEN ADEN
                    / MAXR STOP=15;
ENDSAS;
************************************************************************;
*     END OF PROGRAMME                                                 *;
************************************************************************;
```

Appendix F: Summary of Total Durations For Patterson's 110 Problem Set

Problem No	Talbot	Super Project	Timeline	Harvard II	Primavera	Primavera (SBL)	Micro Planner
1	19	19	19	19	19	19	21
2	7	7	8	8	9	8	7
3	20	23	22	23	23	23	23
4	6	6	6	6	6	6	6
5	7	7	7	7	7	7	7
6	8	8	8	8	8	8	8
7	8	8	8	11	11	8	8
8	11	11	13	11	14	11	11
9	19	21	21	19	25	31	21
10	14	14	14	14	14	14	14
11	18	18	18	18	18	18	18
12	13	14	13	14	13	14	13
13	20	25	27	25	23	27	22
14	43	43	43	45	43	47	44
15	43	43	43	43	45	43	44
16	32	34	33	40	37	45	33
17	29	32	31	30	34	34	31
18	41	45	45	53	47	45	48
19	31	32	33	32	34	34	31
20	37	37	37	37	39	40	37
21	48	52	52	58	52	58	58
22	36	38	38	38	40	44	37
23	32	34	35	39	36	33	34
24	40	41	41	41	42	47	41
25	33	33	33	34	33	33	33
26	43	50	49	50	50	48	48
27	36	37	39	39	41	45	37
28	43	49	47	56	50	48	50
29	29	32	32	38	35	35	31
30	32	33	32	34	35	36	34
31	35	37	37	36	41	41	39
32	22	24	24	28	24	26	25
33	31	34	34	33	35	35	35
34	30	35	35	34	36	34	36
35	31	33	32	36	35	34	33
36	33	34	33	35	37	34	33
37	28	28	29	31	29	31	29
38	30	31	30	36	33	31	31
39	31	32	35	34	36	34	34
40	31	32	32	34	35	36	32
41	36	47	40	44	40	50	42
42	28	29	29	29	30	30	29
43	41	43	41	41	44	43	43

Problem No	Talbot	Super Project	Timeline	Harvard II	Primavera	Primavera (SBL)	Micro Planner
44	31	31	31	31	36	31	31
45	39	45	41	45	45	48	45
46	33	36	34	36	35	45	36
47	35	38	37	38	42	45	36
48	23	25	25	31	26	31	29
49	18	19	18	21	18	21	18
50	25	28	27	33	29	30	29
51	25	28	27	30	26	29	30
52	27	29	29	31	29	33	29
53	28	29	28	30	30	30	30
54	50	50	50	50	50	50	50
55	29	29	29	29	31	29	29
56	27	27	27	27	27	27	27
57	21	21	21	21	21	21	21
58	35	37	36	40	38	46	36
59	31	33	32	32	33	33	33
60	39	43	40	41	42	45	43
61	36	39	36	39	40	50	40
62	37	42	37	39	41	40	42
63	40	42	43	45	44	43	41
64	37	42	39	43	42	43	39
65	40	43	41	42	42	44	41
66	38	40	39	42	40	40	42
67	27	30	29	30	32	32	34
68	41	44	47	49	43	49	45
69	30	33	31	34	31	33	31
70	31	33	34	34	35	37	33
71	32	36	35	38	35	38	36
72	41	49	46	48	45	49	55
73	36	43	44	45	43	49	47
74	30	31	31	31	38	31	31
75	34	39	35	35	37	39	38
76	43	45	44	44	47	45	45
77	64	76	73	73	70	80	77
78	53	69	62	59	63	62	65
79	45	56	48	49	51	59	55
80	38	40	40	41	42	50	51
81	36	37	38	39	37	37	38
82	34	37	36	36	37	43	36
83	34	36	36	36	36	40	34
84	33	33	33	33	33	33	33
85	31	31	31	31	32	31	31
86	31	31	31	31	32	31	31
87	29	32	29	32	33	35	32
88	40	44	44	42	46	44	41
89	31	32	32	32	35	32	32
90	39	43	41	44	44	46	42

Problem No	Talbot	Super Project	Timeline	Harvard II	Primavera	Primavera (SBL)	Micro Planner
91	35	40	36	42	41	41	36
92	28	30	29	31	33	30	28
93	26	28	26	33	29	35	31
94	36	41	38	38	40	42	38
95	33	33	33	40	37	38	34
96	26	27	28	30	28	33	30
97	30	33	31	32	34	32	33
98	41	45	42	51	45	45	46
99	37	42	38	43	38	43	41
100	33	37	37	41	40	42	39
101	75	80	79	81	80	90	83
102	83	85	83	85	83	97	83
103	56	58	58	58	58	58	56
104	79	79	79	80	79	79	80
105	76	77	77	77	77	86	77
106	60	62	63	61	64	63	66
107	78	78	78	78	78	79	78
108	61	64	65	65	63	71	63
109	60	64	63	65	63	62	64
110	50	53	51	65	52	69	54
Total:	3835	4117	4029	4219	4184	4382	4141
% Above Optimal:	0	7.35	5.06	10.01	9.10	14.26	7.98

Appendix G: Summary of Total Duration Percentage Deviations From Optimal

Problem No	Super Project	Timeline	Harvard II	Primavera	Primavera (SBL)	Micro Plan	Average Dev.	STD Dev.
1	0.0	0.0	0.0	0.0	0.0	10.5	1.8	0.0
2	0.0	14.3	14.3	28.6	14.3	0.0	14.3	10.1
3	15.0	10.0	15.0	15.0	15.0	15.0	14.0	2.2
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	37.5	37.5	0.0	0.0	15.0	20.5
8	0.0	18.2	0.0	27.3	0.0	0.0	9.1	12.9
9	10.5	10.5	0.0	31.6	63.2	10.5	23.2	25.1
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	7.7	0.0	7.7	0.0	7.7	0.0	4.6	4.2
13	25.0	35.0	25.0	15.0	35.0	10.0	27.0	8.4
14	0.0	0.0	4.7	0.0	9.3	2.3	2.8	4.2
15	0.0	0.0	0.0	4.7	0.0	2.3	0.9	2.1
16	6.3	3.1	25.0	15.6	40.6	3.1	18.1	15.2
17	10.3	6.9	3.4	17.2	17.2	6.9	11.0	6.2
18	9.8	9.8	29.3	14.6	9.8	17.1	14.6	8.4
19	3.2	6.5	3.2	9.7	9.7	0.0	6.5	3.2
20	0.0	0.0	0.0	5.4	8.1	0.0	2.7	3.8
21	8.3	8.3	20.8	8.3	20.8	20.8	13.3	6.8
22	5.6	5.6	5.6	11.1	22.2	2.8	10.0	7.2
23	6.3	9.4	21.9	12.5	3.1	6.3	10.6	7.2
24	2.5	2.5	2.5	5.0	17.5	2.5	6.0	6.5
25	0.0	0.0	3.0	0.0	0.0	0.0	0.6	1.4
26	16.3	14.0	16.3	16.3	11.6	11.6	14.9	2.1
27	2.8	8.3	8.3	13.9	25.0	2.8	11.7	8.4
28	14.0	9.3	30.2	16.3	11.6	16.3	16.3	8.2
29	10.3	10.3	31.0	20.7	20.7	6.9	18.6	8.7
30	3.1	0.0	6.3	9.4	12.5	6.3	6.3	4.9
31	5.7	5.7	2.9	17.1	17.1	11.4	9.7	6.9
32	9.1	9.1	27.3	9.1	18.2	13.6	14.5	8.1
33	9.7	9.7	6.5	12.9	12.9	12.9	10.3	2.7
34	16.7	16.7	13.3	20.0	13.3	20.0	16.0	2.8
35	6.5	3.2	16.1	12.9	9.7	6.5	9.7	5.1
36	3.0	0.0	6.1	12.1	3.0	0.0	4.8	4.6
37	0.0	3.6	10.7	3.6	10.7	3.6	5.7	4.8
38	3.3	0.0	20.0	10.0	3.3	3.3	7.3	8.0
39	3.2	12.9	9.7	16.1	9.7	9.7	10.3	4.8
40	3.2	3.2	9.7	12.9	16.1	3.2	9.0	5.8
41	30.6	11.1	22.2	11.1	38.9	16.7	22.8	12.2
42	3.6	3.6	3.6	7.1	7.1	3.6	5.0	2.0
43	4.9	0.0	0.0	7.3	4.9	4.9	3.4	3.3

Problem No	Super Project	Timeline	Harvard II	Primavera	Primavera (SBL)	Micro Plan	Average Dev.	STD Dev.
44	0.0	0.0	0.0	16.1	0.0	0.0	3.2	7.2
45	15.4	5.1	15.4	15.4	23.1	15.4	14.9	6.4
46	9.1	3.0	9.1	6.1	36.4	9.1	12.7	13.4
47	8.6	5.7	8.6	20.0	28.6	2.9	14.3	9.7
48	8.7	8.7	34.8	13.0	34.8	26.1	20.0	13.6
49	5.6	0.0	16.7	0.0	16.7	0.0	7.8	8.4
50	12.0	8.0	32.0	16.0	20.0	16.0	17.6	9.2
51	12.0	8.0	20.0	4.0	16.0	20.0	12.0	6.3
52	7.4	7.4	14.8	7.4	22.2	7.4	11.9	6.6
53	3.6	0.0	7.1	7.1	7.1	7.1	5.0	3.2
54	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
55	0.0	0.0	0.0	6.9	0.0	0.0	1.4	3.1
56	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
57	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
58	5.7	2.9	14.3	8.6	31.4	2.9	12.6	11.4
59	6.5	3.2	3.2	6.5	6.5	6.5	5.2	1.8
60	10.3	2.6	5.1	7.7	15.4	10.3	8.2	4.9
61	8.3	0.0	8.3	11.1	38.9	11.1	13.3	14.9
62	13.5	0.0	5.4	10.8	8.1	13.5	7.6	5.2
63	5.0	7.5	12.5	10.0	7.5	2.5	8.5	2.9
64	13.5	5.4	16.2	13.5	16.2	5.4	13.0	4.4
65	7.5	2.5	5.0	5.0	10.0	2.5	6.0	2.9
66	5.3	2.6	10.5	5.3	5.3	10.5	5.8	2.9
67	11.1	7.4	11.1	18.5	18.5	25.9	13.3	5.0
68	7.3	14.6	19.5	4.9	19.5	9.8	13.2	6.8
69	10.0	3.3	13.3	3.3	10.0	3.3	8.0	4.5
70	6.5	9.7	9.7	12.9	19.4	6.5	11.6	4.9
71	12.5	9.4	18.8	9.4	18.8	12.5	13.8	4.7
72	19.5	12.2	17.1	9.8	19.5	34.1	15.6	4.4
73	19.4	22.2	25.0	19.4	36.1	30.6	24.4	6.9
74	3.3	3.3	3.3	26.7	3.3	3.3	8.0	10.4
75	14.7	2.9	2.9	8.8	14.7	11.8	8.8	5.9
76	4.7	2.3	2.3	9.3	4.7	4.7	4.7	2.8
77	18.8	14.1	14.1	9.4	25.0	20.3	16.3	5.9
78	30.2	17.0	11.3	18.9	17.0	22.6	18.9	6.9
79	24.4	6.7	8.9	13.3	31.1	22.2	16.9	10.5
80	5.3	5.3	7.9	10.5	31.6	34.2	12.1	11.1
81	2.8	5.6	8.3	2.8	2.8	5.6	4.4	2.5
82	8.8	5.9	5.9	8.8	26.5	5.9	11.2	8.7
83	5.9	5.9	5.9	5.9	17.6	0.0	8.2	5.3
84	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
85	0.0	0.0	0.0	3.2	0.0	0.0	0.6	1.4
86	0.0	0.0	0.0	3.2	0.0	0.0	0.6	1.4
87	10.3	0.0	10.3	13.8	20.7	10.3	11.0	7.5
88	10.0	10.0	5.0	15.0	10.0	2.5	10.0	3.5
89	3.2	3.2	3.2	12.9	3.2	3.2	5.2	4.3
90	10.3	5.1	12.8	12.8	17.9	7.7	11.8	4.7
91	14.3	2.9	20.0	17.1	17.1	2.9	14.3	6.7

Problem No	Super Project	Timeline	Harvard II	Primavera	Primavera (SBL)	Micro Plan	Average Dev.	STD Dev.
92	7.1	3.6	10.7	17.9	7.1	0.0	9.3	5.4
93	7.7	0.0	26.9	11.5	34.6	19.2	16.2	14.2
94	13.9	5.6	5.6	11.1	16.7	5.6	10.6	5.0
95	0.0	0.0	21.2	12.1	15.2	3.0	9.7	9.4
96	3.8	7.7	15.4	7.7	26.9	15.4	12.3	9.2
97	10.0	3.3	6.7	13.3	6.7	10.0	8.0	3.8
98	9.8	2.4	24.4	9.8	9.8	12.2	11.2	8.0
99	13.5	2.7	16.2	2.7	16.2	10.8	10.3	7.0
100	12.1	12.1	24.2	21.2	27.3	18.2	19.4	7.0
101	6.7	5.3	8.0	6.7	20.0	10.7	9.3	6.0
102	2.4	0.0	2.4	0.0	16.9	0.0	4.3	7.1
103	3.6	3.6	3.6	3.6	3.6	0.0	3.6	0.0
104	0.0	0.0	1.3	0.0	0.0	1.3	0.3	0.6
105	1.3	1.3	1.3	1.3	13.2	1.3	3.7	5.3
106	3.3	5.0	1.7	6.7	5.0	10.0	4.3	1.9
107	0.0	0.0	0.0	0.0	1.3	0.0	0.3	0.6
108	4.9	6.6	6.6	3.3	16.4	3.3	7.5	5.1
109	6.7	5.0	8.3	5.0	3.3	6.7	5.7	1.9
110	6.0	2.0	30.0	4.0	38.0	8.0	16.0	16.7
Average:	7.1	5.2	10.4	9.9	14.1	7.7		
Std.Dev:	6.5	5.6	9.4	7.4	11.9	7.9		

Appendix H: Summary of Variables Included in Total Duration Regression Models

MODELS' NUMBER	VARIABLES NAMES	Tal	Sup	Tim	Har	Pr1	Pr2	Mic
1	SADUR	X	X	X	X	X	X	X
2	SADUR	X	X	X	X	X	X	X
	ACONMX	X	X	X	X	X	X	X
3	SADUR	X	X	X	X	X		X
	ACONMX	X	X	X	X	X		X
	COMPLX	X						
	OFACTT		X	X	X	X		X
	UTLMAX						X	
	MAXNOO						X	
	MINNOU						X	
4	OFACTT	X	X	X	X	X	X	
	MAXNOU	X	X	X		X	X	
	MINNOO	X						
	UTLMAX	X					X	
	SADUR		X	X	X	X		X
	ACONMX		X	X	X	X		X
	ANOOV				X			X
	MAXNOO						X	
	FFACTT							X
5	ACONMX	X	X	X	X	X		X
	OFACTT	X	X	X	X	X	X	
	MAXNOU	X	X	X	X	X		
	ASLRAT	X		X			X	
	MINNOO	X						
	SADUR		X	X	X	X		X
	ANOOV		X			X		X
	ARLFMX				X			
	UTLMAX						X	
	MAXNOO						X	
	MINNOU						X	
	CONAVG							X
	TCONMN							X

Legend: Tal = Talbot's Optimiser
Sup = Super Project
Tim = Timeline
Har = Harvard
Pr1 = Primavera
Pr2 = Primavera (SBL)
Mic = Microplanner Professional

Appendix I: Summary of Variables Included in Total Duration Deviation From Optimal Regression Models

MODELS' NUMBER	VARIABLES NAMES	Sup	Tim	Har	Pr1	Pr2	Mic
1	OFACTT	X					
	UTLMAX		X				
	PERCON			X	X		X
	FFACTN					X	
2	OFACTT	X					
	FFACTN	X				X	
	UTLMAX		X				
	PDENF		X				
	COMPLX			X			
	FFACTX			X			
	PERCON				X		
	ARLFMX				X		
	AADUR					X	
	MAXNOO						X
	ANOUN						X
3	OFACTT	X					
	FFACTN	X				X	
	ACONMN	X					
	UTLMAX		X				
	PDENF		X				
	COMPLX		X	X			
	FFACTX			X			
	PFRSLK			X			
	PERCON				X		
	ARLFMX				X		
	NARC				X		
	AFRSLK					X	
	ACONMX					X	
	ACONVR						X
	MINNOU						X
	SADUR						X
4	OFACTT	X					
	ACONMN	X					
	FFACTN	X				X	
	AADUR	X					
	ATLSLK		X				
	AUTIL		X				
	PDENF		X				

		Sup	Tim	Har	Pr1	Pr2	Mic
	PFRSLK		X	X			
	FFACTX			X			
	COMPLX			X			
	ARLFMX			X	X		
	NARC				X		
	ARLFSM				X		
	PERCON				X	X	
	AFRSLK					X	
	ACONMX					X	
	SADUR						X
	PTLSLK						X
	ACONVR						X
	MINNOU						X
5	ASLRAT	X					
	OFACTT	X					
	AADUR	X					
	ACONMN	X					
	FFACTN	X				X	
	PFRSLK		X				X
	AUTIL		X				
	CONMIN		X				
	TCONMX		X				
	PDENF		X				
	VADUR			X			
	COMPLX			X			
	PTLSLK			X		X	X
	FFACTX			X			
	ARLFAV			X			
	ARLFMX				X		
	NARC				X		
	PCTMAX				X		
	ARLFSM				X		
	PERCON				X		
	ACONMX					X	
	AFRSLK					X	
	CONVAR					X	
	ACONVR						X
	SADUR						X
	MINNOU						X

<u>Legend</u>: Sup = Super Project
Tim = Timeline
Har = Harvard
Pr1 = Primavera
Pr2 = Primavera (SBL)
Mic = Microplanner Professional

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Vita

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13. ABSTRACT *(Maximum 200 words)*

This research investigates scheduling performances of commercial project management software. It is based on difficulties that the Royal Australian Air Force experienced in evaluating microcomputer-based packages in maintenance task scheduling of aircraft undergoing Depot Level Maintenance. A literature review found only one paper quantifying commercial software performances. No standard performance metrics or test data were found. Several packages were evaluated using a common set of 110 single-project resource-constrained networks. The performance measure used was closeness to optimally minimum Total Durations. No package performed best on all problems. On average, the best produced schedules 5.2% longer than optimal, with 95 of 110 problems 0% to 10% above optimal, and values ranging from 0% to 35%. To describe software performance in terms of network characteristics, a linear regression model was proposed. A highly satisfactory fit was obtained using only 2 of the 58 network measures: SADUR (sum of all task durations) and ACONMX (resource constrainedness). Most project scheduling software is written and used assuming task durations have negligible variability, despite contrary industry experience. Rudimentary simulations examined solutions' robustness in a dynamic environment. The results indicate that actual projects will, on average, run longer than optimal deterministic schedules.

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